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Final Degree Project

"Construction of a robotic hand for myoelectric control systems research applied to low-cost prostheses."

Bachelor's Degree in Biomedical Engineering

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1. Abstract

In this project, the construction of an anthropomorphic low-cost robotic hand has been developed to demonstrate its viability and functionality in views to be employed as prosthesis. It is also being used as basis for investigating noninvasive and effective myoelectric control systems.

To this end, a 3D printer has been utilized to print all the component parts of the hand. This process minimizes the costs to obtain a product accessible to everyone, including developing countries.

Then, the components have been assembled and a system of motorization has been implemented for the human hand can perform typical human activities as grasping and pointing.

Finally, a control system based on the blocks tool from Simulink has been designed and implemented, achieving the desired effects: controlling the independent movement of each finger and even of the swivel wrist.

Keywords: prosthetics, robotics, bionics, hand, 3D printer, disability, amputee, anthropomorphism, degrees of freedom, servomotor, Simulink, developing country.

2. Introduction

The main theme of this project is robotics in prosthetics, one of the areas in which there have been more promising developments in the relationship between engineering and health. This field has received increasing attention over the years.

The robotic prostheses can be defined as artificial elements having some autonomy and intelligence, capable of performing functions of a missing body part. Such autonomy and intelligence are achieved by integrating sensors, processors, actuators and complex control algorithms in a coordinated manner.

2.1. Motivation

The amputation does not only imply the inability to perform certain activities, but also means a huge psychological shock. It is true that society should not be designed only for people without functional diversity, but although there is notable progress regarding accessibility during recent years, still today most public services, jobs, classrooms, etc., just adapt to specific characteristics that are supposed to have most of people, meaning that they do not have a completely universal design. So, for many of amputees, the insertion of a prosthesis in place of the lost limb supposes a key point in improving their quality of life.

Bionic prosthetic legs and arms already exist, and to a lesser extent, also hands. In the latter case, achieving that the hand reproduces the functions and actions in the same way as a human hand does, is highly complex due to its high accuracy and sophistication.

The human hand is a complex with a lot of number of degrees of freedom (DOFs). It is capable of both delicate and precise manipulation and power grasping of heavy objects. For this purpose, proprioceptive and exteroceptive sensors are required, whose implementation is a difficult task for designing a prosthetic hand. Sensory capability allows us, among other things, recognizing objects simply by their touch and shape even without seeing them. Quoting Aristotle: “the hand is the tool of the tools” (1).

Summarizing, it can be highlighted that a human hand has:

- 22 DOFs controlled by about 38 muscles in the hand.
- 17,000 tactile units of 4 different types with different receptive fields and different sensitivity to static and dynamic events (2).

On the other hand, commercial prosthetic hands are unable to deliver sensory-motor information to the user. This is a huge limitation in daily use of a prosthetic hand, since the user only can judge by sight when to move or stop the artificial hand. Other problems that present current prosthetic hands are the low grasping capabilities (for instance, they do not allow adequate encirclement of objects compared to the adaptability of the human hand) and the non-cosmetic and unnatural appearance (usually cosmetic devices have no a real functionality).

These problems are caused by the lack of enough degrees of freedom. Until now, achieving more than two active DOFs for prosthetic hands is a difficult task. A possible solution to overcome this limitation could be the redesign of the hand using microactuators. However, another issue appears: the control of many DOFs by the subject. Using complex coding of movements requires a high level of training, which is not desirable. Users should spend a large portion of energy just controlling the hand and without leading a normal life. This lack of a non-fatiguing command interface does not enable a long-term use of the prosthetic hand.

Focusing on the problem of reproducing the degrees of freedom of a human hand, it is found that one of the biggest drawbacks is actuators of a robotic hand. Currently, they are used as actuators: joint servomotors, motors pulling cables that work such as muscles and tendons, or muscles of compressed air. The common problem of all these systems is the weight and size of them. Since it is needed a large number of actuators to reproduce the number of degrees of freedom of the human hand, there are too bulky and heavy hands, used in research and in certain robots, but nothing useful regarding robotic prostheses (3).

All these limitations cause the cost of current robotic prostheses is very high. So, the main incentive of this project is solving this problem by using new manufacturing techniques like 3D printing. This technology has impacted enormously on the world of prostheses and, in particular, on prostheses for children. As the child grows, the prosthesis has to be changed, with the high cost that this entails. However, thanks to 3D printers, building a new prosthesis for the child consists simply of printing larger pieces.

2.2. Historical context

Regarding the history of prostheses, it is found that ancient Egypt people started using prosthetic limbs. Then, Greek and Roman soldiers replaced their lost member in a battle, with an iron arm or a wooden foot. However, they could only function as a cosmetic replacement.

Figure 1. Foot prosthesis used by the ancient Egyptians (Capua, 950-750 B.C.; British Museum of London) (4)

Figure 2. Replica of a Roman leg (about 300 B.C.; Science Museum of London) (5)

In the Modern Age, a German mercenary and poet named Gottfriend "Götz" von Berlichingen was a pioneer in useful artificial hands. In 1504, because of the siege of Landshut, a German city, Berlichingen lost his right arm and used a prosthetic iron replacement that was capable of holding objects. It was able to move by using a series of gears and catches.

The artificial hand worn by Berlichingen is today on display at the Jagsthausen Castle in Germany. It is shown its design in the next figure:

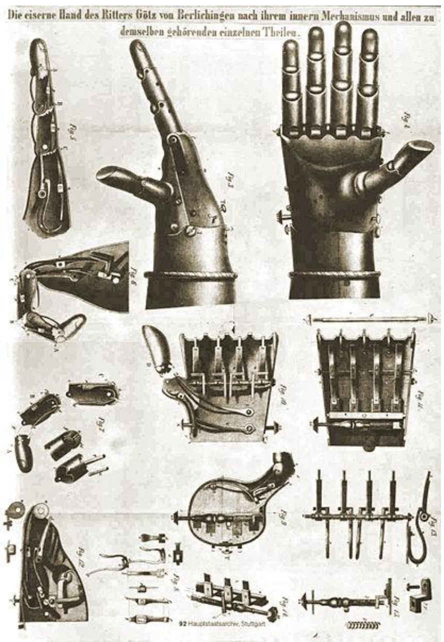


Figure 3. Berlichingen's hand (6)

Another jump in this field was carried out by Marcel Desoutter (1894-1952), an English aviator who had a flying accident and lost his leg. Along with his brother, he created a company to manufacture prosthetic limbs. For instance, they developed the first aluminum prosthetic hand (7).

Finally, in the past century, prosthesis technology has advanced by leaps and bounds. Nowadays, there are bionic hands using microprocessor technology to resemble a fully functional human hand. Also modern cosmetics play an important role in order to make the amputee to feel more comfortable.

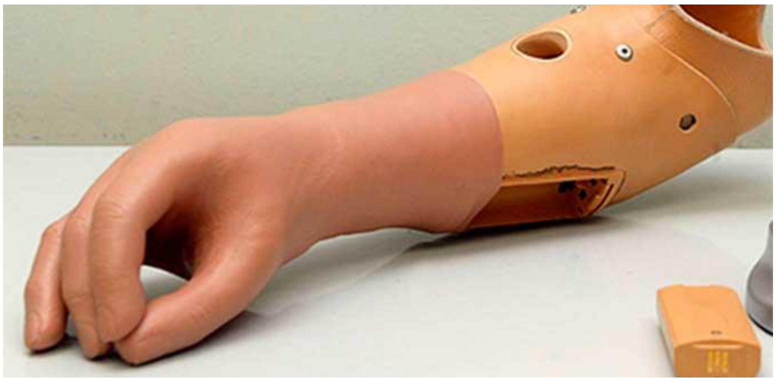


Figure 4. Example of contemporary hand prosthesis

2.3. Objectives

Since the proposed project and performed work have been major challenges, two people have been working simultaneously in order to solve all fronts. In this way, the whole project has been divided into two distinct parts. Although they can be treated and analyzed independently, are, of course, closely related and cannot be fully understood if they are not seen together as a single project.

The final degree project that reflects what would be the second part of this one, is titled: “Implementation of a neural network-based electromyographic control system for a printed robotic hand”, and has been written by my colleague Irene Mendez Guerra (8).

It describes the high-level control based on EMG signals by which an amputee could move prosthesis in a simple and intuitive way.

Thus, the general objectives of this first part of the project are manufacturing of a robotic hand, and implementation and developing of low-level control systems with a view to the integration of high-level control systems. Specifically, the desirable specifications expected to achieve into the robotic hand are as follows:

- Low cost and simplicity.
- Anthropomorphic shape and configuration.
- Reduced weight and size.
- Minimum quantity of actuators.
- Independent control system.
- Maximum functionality.
- Human abilities such as grasping and pointing.
- Minimal invasiveness.
- Integration with high-level control systems.
- Viable and sustainable development.

The most important feature to take into account is the low cost, since current commercial prostheses are accessible only to a minimal fraction of the population. In addition, paradoxically, in countries where the rate of amputees is higher because of violent conflicts, access to prostheses is much lower than in countries with low demand. The biggest reason for this fact is the high price. Thus, the main goal of this project has been demonstrating the feasibility of creating a robotic and functional prosthesis having low cost and easy adaptability.

2.4. Structure of the document

Until now, the document has only displayed the different indexes, a brief abstract of the whole project and this current introduction. The next chapters are dedicated to the heart of the matter with the following organization:

- **Chapter 3. State of the art**. In this section, the current situation of the subject hereof is described. Also it is shown an overview of the most popular robotic hands and prostheses in the market, and it is explained the relationship between prostheses and the 3D printer. Regarding this tool, theoretical concepts are described. Likewise, it is highlighted the huge opportunity of printed prosthetics in developing countries and the benefits of open source designs.

- **Chapter 4**.**InMoov Hand.** Focalization on the construction of a specific robotic hand called InMoov. All the steps performed to build the hand are detailed and commented alluding to theoretical background.

- **Chapter 5. Low-level control of the robotic hand.** The microcontroller and other necessary tools to control the movement of the hand are defined. Besides, different control models used from Simulink are clarified.

- **Chapter 6. Conclusions.** Some remarks after the whole exposition of the project are drawn.

- **Chapter 7. Future work.** Investigations still pending to make this project more robust and to continue studying how to overcome the present difficulties and limitations, are described.

Finally, all the literature and other useful documents are detailed into the bibliography and the annexes.

3. State of the art

Over the last decades, some engineers began research to address the challenge of designing and building versatile robot hands. Hands are very useful as end effectors for human beings in particular. So, the latest advances in this area show that there is a need for anthropomorphic hands which are light, compact and easy to control. Current trends include low-cost and flexible materials, and synergistic relationship between them (9).

The adjective *anthropomorphic* refers to the feature of the robot hand which makes it similar, in size and shape, to a human hand (10). The level of anthropomorphism can be achieved in various ways and two characteristics are distinguished here: the structure of the hand and the number of fingers.

3.1. Anthropomorphic Robotic Hands

Currently, much effort is placed on developing a variety of robot hands imitating the human ones for performing different operations. Four fingers and an opposable thumb arranged as in a human hand, permit grasping a broad diversity of objects.

So, the robotic hands cited in this project have the same arrangement as a human hand (human-like placement of the finger base frames) and a total of four or five fingers (except for the Barret hand) (11). However, human hands have advanced functions and it is not easy to reproduce their motion. So, robot hands have problems regarding the number of degrees of freedom (DOFs) and versatility (12).

The aforementioned interest is motivated by the fact that robot hands can be used for a number of everyday life applications, ranging from telemanipulation studies, to human robot interaction, for humanoid robots or even as affordable myoelectric prostheses.

Furthermore, two types of robotic hands are distinguished: actuated and underactuated hands. To understand these concepts, two definitions are necessary:

- Degree of freedom: number of independent parameters that define the configuration of a system. In this case, opportunity of an independent movement between two rigid solids.
- Degree of action: number of actuators that act in a system.

According to these definitions, an actuated hand is one that has the same degree of action and degree of freedom; on the contrary, an underactuated hand uses an actuator to move several degrees of freedom. The latter is common due to the criterion of the actuator size, and usually proximal, middle and distal phalanges are joined by an only actuator. In this way, one actuator moves three degrees of freedom (13).

The following is an introduction of some commercial robot hands (DLR, shadow…) to illustrate the previous exposition and to analyze the state of the art of this area.

3.1.1. DLR Hands

DLR is the national aeronautics and space research center of the Federal Republic of Germany. The Robotics and Mechatronics Center (RMC) is a cluster and DLR's competence center for research and development in the areas of robotics, mechatronics, and optical system; which include robot hands field. The official website of the center (14) offers a short list with an illustrative photo of hands that have been developed:

- **DLR Hand II**

DLR Hand II consists of four fingers with four joints and three DOFs each. An additional degree of freedom in the palm allows the hand to adjust perfectly for either stable grasping or fine manipulation. It was rated as one of the most advanced and complex artificial hands in the world when it was introduced in 2001.

Figure 5. DLR Hand II (14)

- **Hit Hand II**

The DLR-HIT Hand II is used as a tool on Space Justin (an autonomous and programmable humanoid robot) by telemanipulation for grasping objects with shared autonomy. It has four joints and three active DOFs. So, the human operator can perform a lot of manipulation tasks with this robot hand (15).

Figure 6. Hit Hand II (14)

- **DEXHAND**

A hand built to withstand the harsh environment in space that could help to repair defect satellites. It is an excellent support for astronauts during maintenance and hazardous tasks. Through telemanipulation control, this hand can manipulate most of the EVA (Extra Vehicular Activities) tools.

Figure 7. DEXHAND (14)

- **Hand from Hand-Arm System**

The particularity of this hand is that the actuators and sensors are located in the forearm of the system. This allows building a hand with the size and dexterity of a person.

Figure 8. Hand from Hand-Arm System (14)

From this list, the last one can be highlighted as it is still the most complex mechatronics hand in the world with 38 motors and 19 DOFs. The experience of DLR of more than 20 years designing and building robotic hands makes it unique in size and performance with respect to human archetype. The main focus of this development is placed on robustness, dynamic performance and dexterity. For this goal, every joint is composed of two motors. Mechanically, a nonlinear spring mechanism coupled to the tendons permits the hand to receive a feedback of the position and passive joint stiffness at the same time. The robustness is due to the decoupling from the gear and output, which resists strong hits (16).

3.1.2. Shadow Hand

The Shadow Dexterous Hand is an anthropomorphic robot with 20 actuated DOFs, absolute position and force sensors. The hand can be controlled by teleoperation and can be part of a bigger robot system. However, it is a self-contained system since all actuation and sensing parts are built into the forearm and hand.

The nearest characteristic to human abilities is the possession of ultra sensitive touch sensors and Pressure Sensor Tactiles (PSTs) on the fingertips. They allow detailed force, microvibration and temperature gradient sensing.

On the other hand, it proffers force output and movement precision similar to those provided by a natural human hand. For this purpose, the hand includes force sensing for each actuator, temperature and motor current and voltage sensing. A separate force sensor measures the force in each of the pair of tendons driven by the Smart Motor unit. This data is captured by 12-bit ADCs and used locally for torque control. A Hall effect sensor senses the rotation of each joint locally with 0.2 degrees typical resolution. All this data is recorded to ensure safety and reliability.

These hands use two different actuation systems: an electric “Smart Motor”, integrating force, position, and motor drive electronics; and a pneumatic “Air Muscle” actuation system, integrating pressure and position control electronics.

The Shadow Hand has been used for research in manipulation, neural control, grasping, brain-computer interface, industrial quality control and hazardous material handling.

This advanced humanoid robot hand provides twenty-four movements in order to reproduce as closely as possible the human hand in kinematics and dexterity. Each joint has a movement range identical to or very similar to that of a human hand, including the thumb and even the flex of the palm for the little finger.

The hand and forearm have a total weight of 4.2 kg and are composed by a combination of metals and plastics including aluminum, brass, acetyl, polycarbonate and polyurethane flesh. The models containing "Air Muscle" system have additional materials including rubber, nylon and cork.

Regarding the consumption, power supplies are provided with the hand. The part of the motor and the part of the air muscle consume energy at a different rate which should be taken into account. (17)

Figure 9. Shadow Hand (17)

3.1.3. Barret BH8-282

The BH8 Barrett is a programmable multi-fingered hand with the ability to secure the grip of objects of different sizes, shapes and orientations. Of its three multi-jointed fingers, two have an extra DOF with 180 degrees of lateral mobility supporting a large variety of grasp types. Moreover, all the joints have high-precision position encoders.

Despite its light weight (980 grams) and compact form (25 mm), it is completely self-contained. The series BH8 Barrett integrates CPI, software, communication electronics, servo controllers and 4 brushless motors.

This model allows the integration with any arm in a quick and simple way. The BH8 series immediately multiplies the value of any arm requiring flexible automation.

The Barrett Hand takes advantage of a versatile software routine and achieves the functionality of an endless set of custom grippers. It is a single smart grasper shipped as a complete turn-key system.

The control application works under both Linux and Windows and presents an easy-to-use graphical user interface (GUI) to move the Barrett Hand. The graphical environment permits the user to learn without writing any code (18).

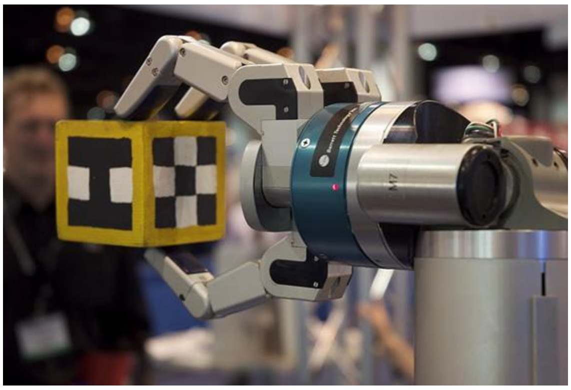


Figure 10. Barret BH8-282 (18)

3.1.4. iCub Hand

The iCub hand is part of a whole humanoid, an open source robotic platform funded by the European Commission. The main design goal was the necessity of studying complex daily skills such as grasping or manipulation. The hand has 20 joints organized in 9 degrees of freedom (using 9 DC motors) and the dimensions were inspired by those of a human. The hand also has 12 tactile sensors at each fingertip, 48 pressure sensors based on capacitive technology in the palm and 17 position sensors (in 17 out of 20 hand joints).

The hand actuation system is based on tendons, a good solution for a reduced space. The degrees of freedom of the hand are actuated by motors which are embedded in the forearm (only 2 motors are housed in the palm) and controlled by control boards located in the upper arm. The tendons associated to the motors are routed through the wrist. Therefore, certain DOFs are obtained by coupling different joints (either tightly or elastically) so that they are moved by a single motor in a synergistic fashion (19).

Figure 11. iCub Hand (19)

3.2. Robotic Prostheses

As seen in the previous section, robotic hands that can perform more functions have an anthropomorphic configuration. So, the idea that they could serve as prostheses for amputees was quickly suggested (20).

In the prosthesis field, two principal features are taken into account to select the most adequate artificial limb for each person: appearance and functionality. Most prostheses sacrifice some degree of one for the other. Because of this, there are purely cosmetic (but inert) prostheses and functional ones (with mechanical appearance). However, myoelectric prostheses are an attempt to serve both purposes of an artificial limb equally, without sacrificing appearance for functionality.

Depending on the posterior application of the prosthesis and some other criteria, different types of control can be selected:

- By harness (body-powered).
- By tendon activated pneumatic (TAP) foam sensors.
- By Hall effect sensors.
- By direct tunnel muscle cineplasties, in an extension of the extended physical proprioception (EPP) concept.
- By EMG.

Traditional prostheses are mainly body-powered, which means that they work by using cables to link the movement of the body to the prosthesis and to control it. This process can be fatiguing, so an externally-powered artificial limb might suppose a solution to this physical exertion through using a battery and an electronic system to control movements. At the forefront of this technology is the myoelectric prosthetic, which provides more range of motion, a larger functional area, greater comfort and a more natural appearance. However, they cost and weigh more because of the motors and the battery contained inside. With time, as technology develops, the weight of the components will become lighter and cheaper to produce. In addition, hybrid prostheses combining different types of control like myoelectric components and body-powered components also exist.

A prosthesis controlled by electromyography is an externally powered artificial limb that can be dominated with electrical signals generated naturally by muscles. The connection of the prosthesis and the residual limb is carried out via custom fabricated socket and the suction created between it and a donning sock with maximum suspension.

Current myoelectric-controlled prostheses offer an electronic system very similar to a human hand or arm (21). They are designed to mimic motion and human anatomy with a natural appearance. So, when covering the prosthesis with a skin-like glove, a human appearance is well achieved.

The mechanism of myoelectric prostheses consists of using the existing muscles located in the residual limb to control their motion. To do so, several sensors are fabricated into the prosthetic socket in order to receive electrical signals from the muscles (EMG activity). These signals depend (in frequency, amplitude, etc.) on the motion that the user wants to perform, since the muscle intensity determines the strength and speed of the prosthetic movements. The end result is that the artificial limb moves much like a natural limb, according the mental stimulus of the user. To the outside observer, it looks like the person is moving the hand or the arm with his own thoughts.

Then, the data obtained by the sensors is released to a controller, which translates the information into commands for the electric motors. In this way, prosthetic joints move according to the desire of the patient through electrical signals, even allowing him or her, the manipulation and grasping of small objects with precision through functioning fingers. These hands can lug a suitcase or hold an egg without cracking it. They are not as good as a natural hand, but they come pretty close.

For people who have no residual limb or have muscle or nerves damaged, other parts of the body like the chest or the back can be used to control the movement of the prosthesis. There are hands which are particularly useful when muscles produce limited or difficult to control signals, as is often the case with higher-level amputation. Nevertheless, most of times, a unique muscle produces the motion of several joints, which means less accuracy but more ease to control the whole prosthesis.

To conclude this section, it can be mentioned that myoelectric prostheses need an external power supply to feed motors and electronics. The best solution is a battery; there are two main types: removable and non-removable, depending on how they are charged.

In the succeeding paragraphs, some hand prostheses from the current market which are controlled by myoelectric signals will be introduced.

3.2.1. The i-limb Hand

This first model is called i-limb ultra and was manufactured by Touch Bionics, a provider that solely manufactures upper limb prosthetic devices and is committed to providing the most innovative technologies. Invented by David Gow and his team, it was the world's first commercially available bionic hand launched in Vancouver (Canada) in July 2007.

This prosthesis looks and moves like a natural human hand. Individually motorized digits have the ability to articulate allowing the hand to bend at the joints of each digit. So, the hand accurately conforms to the shape of the object being grasped by rotating the thumb.

Traditional myoelectric devices provide only one grip pattern which should generate a stronger-than-human grip force at the tip, where the fingers meet with the object, in order to successfully hold heavy or odd-shaped items. Instead, the i-limb ultra permits the wearer to increase the strength of the grip around an object, and there is a function to prevent objects from slipping. This fact can be very useful in situations where a firmer grasp is required, such as opening a tightly closed bottle or jar.

As most of the hands from the market, a natural skin-like covering is included to provide a human appearance. This aspect is also achieved when the hand automatically moves to a natural position after a period of inactivity. The difference with the real limb is going gradually reduced since the prosthesis can perform several complex daily tasks such as typing or tying shoelaces with improved control, ease-of-use and accuracy.

Regarding the consumption, a power management allows extending daily battery usage by 25% and there is a warning audio signal when the percentage is too low. A mobile app also controls these parameters and provides access to fourteen programmable grip patterns (22).

Figure 12. The i-limb Hand (22)

3.2.2. Bebionic Hand

Advertising sells the Bebionic Hand as the most advanced prosthetic hand around the world. RSLSteeper, creator of this artificial hand, is advertised as a way to transform the lives of amputees at a reasonable price. The prosthesis is offered at a price of $11,000 (9.000 €) without including the glove covering the hand ($600). Comparing this quantity from other ones from the market, it does seem to be the least expensive. For example, the Bebionic's price tag is about 35% less than i-Limb, another hand that will be detailed later.

The price is a huge advantage, because as it can be guest, The main reason why most of the amputees use traditional hooks rather than sophisticated prosthetic hands, is that they do not have enough money to buy them. So, even if it is not cheap, is closer to fitting in the budget of the average family.

Encouraging patients to create positive turning points, the brand announces that this advanced system permits them to start using the prosthesis immediately and get comfortable with it in a week.

The bebionic hand provides fourteen different grip patterns, allowing the patients to have a more complete prosthesis to assist them in their daily activities.

The hand has two selectable thumb positions: opposed and non-opposed. The first one places the thumb allowing grips like tripod (with the index and the middle fingers), pinch (the thumb contacting index finger), power (when fingers are approaching a fully closed position, the thumb drives in to cover the fingers for additional grip security) and active index (the position to use, for instance, a spray bottle).

On the other hand, non-opposed position allows grips like key (The thumb then closes onto the side of the index finger), finger point (position to use an tablet), column (moving the thumb into the palm from a non-opposed position) and mouse (the thumb and little finger close to hold the side of the mouse).

There are further functions of the bebionic hand like precision open, precision closed, hook, finger adduction, open palm or relaxed hand.

The combination of all these positions allows users to type, pick up, hold and manipulate a variety of objects (including fine ones), to carry papers or letter, to press a bell, to push heavy barriers, to dress… (23).

Figure 13. Bebionic Hand (23)

Finally, it will be introduced the bebionic glove made from a multi-layered, variable hardness silicone-based material, lined with fabric mesh. This coverage resists soiling, wears and punctures damage, and provides high compliance with gripped objects.

Figure 14. Bebionic glove (23)

3.2.3. Ottobock Hand

Since its founding in 1919 in Berlin, Otto Bock Company pursues the vision of improving the mobility of persons with disabilities through innovative products. For example, the *Michelangelo Hand*, advertised by the enterprise as an “intelligently simple” prosthesis. As important features, it can be highlighted that it is very easy for the user to operate and that the power supply is provided by a system integrated into the socket. Moreover, a silicone glove can cover the hand to achieve a more natural look and feel, and is available in several shades. From the brochure of the system, the following Figure does a summary:

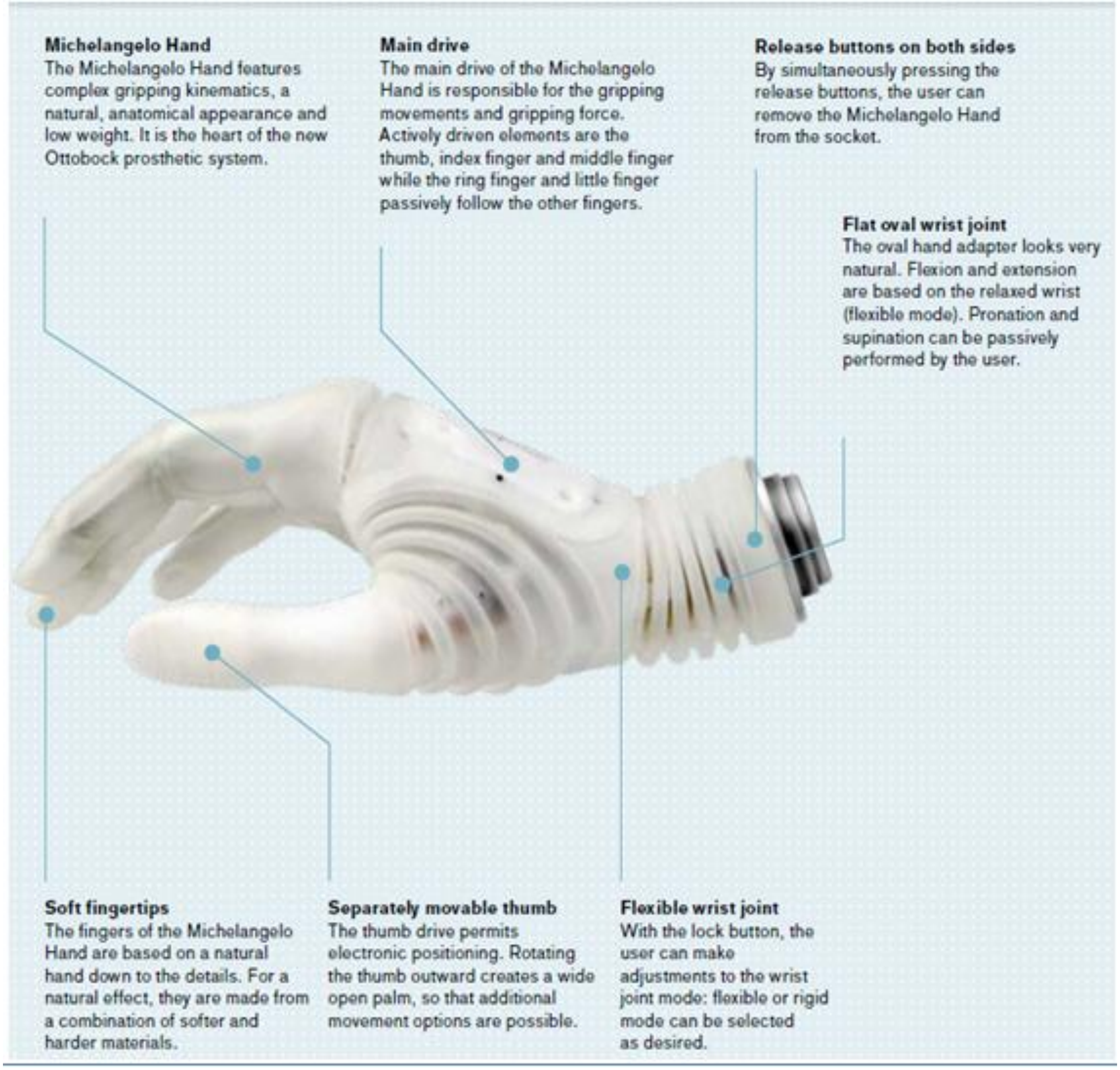


Figure 15. Michelangelo hand from Ottobock (24)

The hand has three fingers actively driven: the thumb, index and middle; the ring and pinky passively follow the previous fingers. So, it is able to support a lot of objects as bottles or drinking glasses. Furthermore, the fingertips are made of a mixture of soft and hard materials to permit real accuracy when grasping objects.

As newness, the hand has the first thumb in the world that can be positioned electronically with myoelectric controls. This fact is due to a second drive unit to control the gripping action (most hand have only a single drive unit to control all the fingers). Thus, the prosthesis offers seven grip types including a powerful key grip and open palm. Also the hand returns to a natural rest position when not being actively used.

3.3. Prosthetic Hands and 3D printing

In this section, it will be explained the fundamentals of 3D printing as well as the impact on the society of this remarkable technology. Then, the connection with prostheses and developing countries will be made.

3.3.1. Introduction to 3D printing

3D printing is a quickly expanding field since the popularity and different applications for 3D printers is growing day by day. It is a manufacturing process that builds layers to create a three-dimensional physical solid object from a previous digital model. The essential tool to perform this operation is the 3D printer, based on additive manufacturing procedures according to the computer code received.

Born on May 12, 1939 in Clifton, Colorado, Charles W. Hull is the inventor of 3D printing process (1986). He went on to launch the world's largest 3D printer manufacturers called 2D systems. However, his invention concentrated only one of the 3D printing technologies: stereolithography (SLA).

While SLA technology becomes more popular by the end of 80s, Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) were introduced in the industry. Progressively, techniques have been developed and now many of the 3D printers are even self-replicating, such as those from *RepRap project* (25). This project has allowed having low-cost printers at home. In this way, buying a 3D printer is a relatively effortless and prompt process; even online retailers sell these types of products.

3.3.2. Functioning

When a model is designed or downloaded, the file should be converted into G-code (or other less important languages), a numerical control computer language. To do so, programs such as *Slic3r* or *Skeinforge* are required. Usually, the files have extensions OBJ, PLY, STL, 3MF, etc.

This mentioned code is indispensable to transfer the 3D model to the printer and communicates the machine how to move to create the piece. So, the 3D printer starts to move according to the instructions and does its performance depending on the technology involved as it will be explained in the following point.

3.3.3. Different technologies

As mentioned previously, different approaches exist to create objects using additive methods. The most common are explained in the following paragraphs.

- *Stereolithography (SLA):* the first additive manufacturing technology and in the process of expiring over the next years because of the competition with other techniques and the price. However, SLA products usually achieve better accuracy and appearance than others pieces.

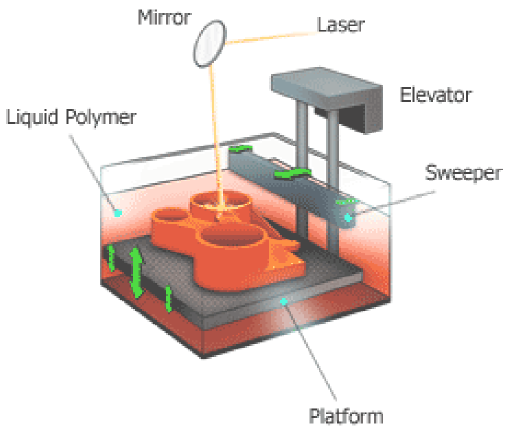


Figure 16. SLA 3D printer

The SLA procedure works with a laser or DLP (Digital Light Processing) projector combined with a photosensitive resin, instead of extruding a material through the hotend. A perforated platform is placed below the surface of a vat of liquid photo curable polymer. Then, the lighting source slowly traces the first slice of an object on the surface of the liquid and hardens a very thin layer of photopolymer. For the next layer, the platform is lowered and the process is repeated. In this way, the resin is cured layer-by-layer as the object is created, removed from the vat and drained of excess liquid.

- *Fused deposition modeling (FDM) / Fused filament fabrication (FFF):* these names are due to S. Scott Crump, the inventor of the technology, and *Stratasys* which has a trademark on the terms.

Most of non-professional desktop 3D printers utilize FDM/FFF because of the simplicity of its mechanism. Furthermore, the thermoplastic material usually used is ABS (acrylonitrile butadiene styrene), PLA (polylactic acid) or composites of both, all of them easy to find. In fact, this kind of technology is the used for the development of this present project.

The plastic is fed into an extruder and is melt and turned into a gooey liquid. Then, the printer deposits plastic layers until forming the entire object. Each layer is rapidly solidified and serves as a rigid surface for the deposition of the next layer. With this method, the temperature-controlled print head can produce fairly robust objects with a high degree of accuracy through the G-code containing the digital model.

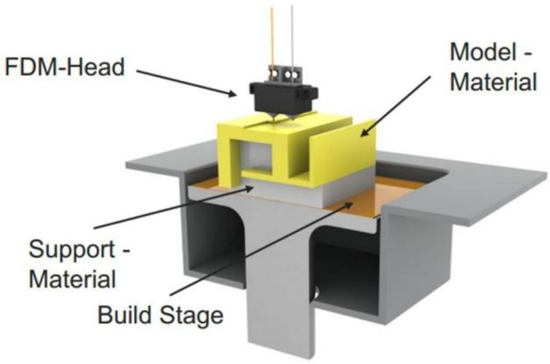


Figure 17. FDM 3D printer

- *Selective laser sintering (SLS) / Direct metal laser sintering (DMLS) / Selective laser melting (SLM).* These techniques are grouped because they are very similar, even having marked differences. Because of this, the terms are not completely interchangeable. For instance, the difference between SLS and DMLS is the material used: SLS refers to the layer-by-layer building of non-metal objects (ceramics, glass, plastics, etc.) while DMLS consists of the same process but with metal powders (especially metal alloys).

  On the contrary, SLM is used when dealing with metals without combinations (there are no different melting points so the molecules could completely melt together).

  Common for the three procedures, a laser is used to fuse materials (wax, metals, nylon or other materials) at molecular level without being melted (only heated). This effect is called sintering: “compacting and forming a solid mass of material by heat and/or pressure without melting it to the point of liquefaction”.

The high powered laser beams required to SLS, DMLS and SLL are highly expensive and, in addition, safety precautions that should be taken mean more costs. This is why abovementioned technologies are more popular.

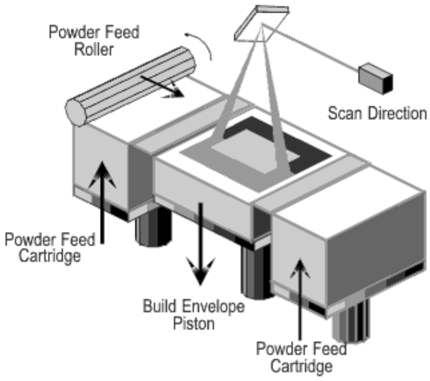


Figure 18. SLS 3D printer

Anyway, all these technologies are currently cheaper and easier to implement within a machine with respect to a few years ago.

3.3.4. Associated software

To carry out the design of parts to be printed in 3D, modeling software is required. There are three main categories: CAD Tools, Freeform Modeling Tools and Sculpting Tools. Whereas the tools of each group can generate models suitable for 3D printing, designs that can be created have different features:

- *CAD (computer-aided design) tools:* are principally based on using geometrical shapes to build digital models. The most common and widely used CAD software are: Blender, FreeCAD, AutoCAD, Catia, OpenSCAD, SolidWorks, TinkerCAD, 3DSlash, 3DTin, CubeTeam, Rhino 3D, etc.

- *Freeform modeling tools:* are based not only on geometrical shapes, but allowing the creation of new, freeform shapes. For example: 123D Creature, 3ds Max, Blender, Cinema 4D, Maya, etc.
- *Sculpting tools:* allow pushing, pulling, pinching and grabbing to form digital models. Several of these tools are: Sculptris, SculptGL, Leopoly, Cubify Sculpt, ZBrush, etc.

Most of these programs are very easy to use, since the interfaces are intuitive for the user.

On the other hand, other kind of software is required to prepare and execute 3D pieces printing: a slicer. The preparation consists of scaling, rotating and placing the model on the print bed. Then, slicing process is needed: the translation to the model into individual layers. It implies the generation of the G-code necessary to feed into the 3D printer. Moreover, slicer programs enable calibration of settings like extrusion and head speeds, the temperature, wall thickness or fill patterns; all of them having a lot of influence on the design.

Finally, control software allows the users to send the code file from the computer to the 3D printer, change some parameters on run time and move the print head manually around the x, y and z axes.

There are some tools than combine slicer and control user interface software such as Simplify3D or Autodesk 3D print. However, other software programs (pure slicers and pure control interfaces) have to be used together to performs the same tasks.

Examples of pure slicers are: *Skeinforge*, *Cura*, *KISSlicer* and *Slic3r*; and of pure control software are: *ReplicatorG* and *Repetier-Host*.

3.3.5. Uses and applications of 3D printed products

Initially, 3D printing was an advantageous system for prototyping since companies could iterate upon designs and mockups, and test ideas on the fly, saving manpower and months of waiting for other persons to return molds. However, currently there are also a lot of end-use products and components via this technology, which permits creating complete models instead of parts for assembly.

In medical field, surgeons and clinicians can touch physical models of human organs or bone structures for research.

In addition, there exist companies creating 3D printed human tissues with hydrogels and living cells for pharmaceutical toxicology testing. Also they have built bone grafts for patients suffering traumatic accidents. Possibly, in the near future, entirely printed organs will be used for transplantation.

In this area, it is included the fabrication of customized prosthetics such as legs, feet, arm or hands, the most interesting matter for this project.

Also in aerospace industry, numerous manufacturers are turning to 3D printing to reduce the weight of the aircraft and the price. Complex geometries and shapes with less mass and new materials offered by 3D printing, allow saving costs of fuel when launching airplanes or rockets.

Figure 19. First 3D printed plane

Figure 20. The plane is able to take flight

Last, 3D printing is a new way to develop the talent of artists, architects and engineers. Converting virtual designs and ideas into physical objects allows better visualizing the concepts and learning through experience working with real systems.

3.3.6. The 3D printing revolution in prosthetics

Among the medical applications of 3D printing, prostheses occupy a very special place. This is mainly due to the reduction of price, waiting times and weight that offer printed prostheses for patients that usually cannot afford them. New emerging technologies provide new solutions to health problems, as in this case.

3D printing allows engineers and doctors can make use of created limbs cheaper and faster than ever before. Anyway, the challenge continues since matching a person with the right prosthesis is complex, but helping amputees improve the quality of their lives is worthy and rewards any effort.

John Rieffel, assistant professor of computer science at Union College in Schenectady, New York, is specialized in 3D printing. Regarding this topic, here are some of his comments: “3D printers allow you to customize in ways we never could before (…). You can print customized prosthetics specialized for one person. This reduces cost because you produce them to order, instead of mass producing them and then sizing them (…). Children grow really quickly. Adults can keep a prosthetic leg designed for them for as long as they want. For children, they grow so often that they need new prosthetics quite often, which can be quite expensive (…). Computers used to be giant machines that filled rooms. Now they’re in our pockets. Today, instead of 3D printers only being for schools and corporations, you can go to Home Depot and pick one up (…). You’ll be able to go online and download existing models for prosthetics, and then print them at home. The possibilities are endless (…). These printers have a ton of potential” (26).

In addition, 3D printing applications in prosthetics are not only about replacing limbs. For people needing implants or facial parts such as an ear, this technology is able to provide an excellent alternative. Furthermore, in the next future, 3D printed replacements of other parts of the body like the hip or the knee will be completely usual.

3.3.7. Prostheses in developing countries

Most of millions of upper limb amputee people live in developing countries where prostheses can be difficult to come by, and rudimentary when available. Lack of infrastructure in poor and rural communities around the world hinders the access to advanced orthopedics (27).

However, with 3D printers and their ease to be transported, a viable solution met the demand for prostheses. By just clicking a button, a 3D printed prosthesis can be obtained within a few hours and tailored for patient's needs. To this end, the creation of low-cost 3D printed prosthetic limbs such as hands, supposes a huge benefit for a very high percentage of the population affected by the absence of a member.

Fortunately, there are associations that aim to expand the availability of prostheses especially for people who need them most. As examples, the following paragraphs show the presentation appearing in official websites of some of these associations:

"E-NABLE is a growing group of over 3600 members who have come together from all over the World to help create and design 3D Printed assistive hand devices for those in need.

We are engineers, artists, makers, students, parents, occupational therapists, prosthetists, garage tinkerers, designers, teachers, creatives, philanthropists, writers and many others – who are devoting our "Free time" to the creation of open source designs for mechanical hand assistive devices that can be downloaded and 3D printed for less than $50 in materials" (28).

Figure 21. Hand provided by E-NABLE (28)

Figure 22. Other hand provided by E-NABLE (28)

"In 2011, 14-year-old Daniel Omar had both his arms torn from his body by a bomb dropped by Sudanese forces on civilians in the Nuba Mountains. On November 11, 2013, Not Impossible's 'Project Daniel' fitted a 3D-printed arm on Daniel that enabled him to feed himself for the first time in 2 years." (29)

Figure 23. Hands from Project Daniel (29)

“The Victoria Hand Project (VHP) designs and develops low-cost, highly functional, upper-limb 3D printed prostheses. In collaboration with our clinical partners, we make these prostheses available to amputees throughout the world. Our system uses advanced and cost effective tools including 3D printing and 3D laser scanning, to fabricate these devices directly within the countries where they are used. With our prosthesis, amputees can regain the ability to do home or work-related tasks, and improve their quality of life. The Victoria Hand Project aims to increase access to upper-limb prosthesis for persons in developing countries” (30).

Figure 24. Victoria Hand (30)

Figure 25. Use of Victoria Hand in the third world (30)

3.3.8. Open source concept

"The term 'open source' refers to something that can be modified and shared because its design is publicly accessible." It can refer to software developments, products, projects, etc.

Open source designs permit researchers to introduce infinite variations and modifications according to different needs. Anyone and anywhere is able to download prototypes and improve them and share once again with other researchers. So, open-source codes are available and anyone can copy them, learn from them, alter them, or share them.

Some licenses ensure that users who utilize an open-source software or project and alter it, then must also share their own work. In this manner, no one should prevent others from doing the same they did. This fact encourages users to customize and share the designs.

Usually, most of people prefer open-source technologies to have more control over the codes, the models, etc. Furthermore, errors can be easily corrected because someone could detect them, so that open-source programs are always upgraded and updated.

Also for students it is highly advantageous as they can learn from others who are experts in the matter (31).

On the other hand, since 3D printing technology is developing so rapidly, open-source models in this context are having a huge impact on medical, aerospace or industry areas. Thus, depending on the intended use of the 3D piece or, more specifically with respect to this project, of the prosthesis, users can choose between a large range of options.

Commercially available robotic prosthetics are often very expensive and difficult to customize (32). However, here it is introduced an open-source, low-cost hand that can be created through accessible 3D printers and off-the-shelf electronic components: the Open Bionics hand.

Open Bionics

Open Bionics is a prosthetics startup which has received the 2015 UK James Dyson Award for design engineering innovation because of a 3D-printed bionic hand. It is an "open-source initiative for the development of affordable, light-weight, modular robot hands and prosthetic devices that can be easily reproduced using off-the-shelf materials" (33).

The material used to print the hands is usually a flexible plastic resistant to falls and bumps. So, while currently available prosthetics for amputees cost between 2,000$ and 60,000$, anthropomorphic prosthetic hands from Open Bionics cost less than 200$ and weigh less than 300g. Also adaptation to the new bionic hand by users lasts only few days in contrast with other alternatives.

As it is observed, anthropomorphism is taken into account since the human hand is the most dexterous and versatile end-effector known. An Anthropomorphic kinematic model and the use of a bio-inspired transmission system reproducing the flexion and extension of fingers, improve performance for daily tasks.

As the hands described in the previous section, the control is carried out by electromyographic sensors detecting muscles contraction. In this manner, users can open or close the hand, or grip different objects.

Regarding the thumb, nine different configurations are allowed with one rotational DOF. Along with the configuration of the other fingers, the proposed model is able to produce, in total, one hundred forty four different grasping patterns.

There are sensors located in the fingers which are able to sense the contact with objects in order to avoid accidents. Designers are also trying to replicate bones and ligaments to give a more natural appearance. The functionality is really important, but the comfort of the patient is a plus. Because of this reason, length and width of each phalange can be modified in order to achieve more personalized prostheses. Each robotic hand is designed to fit the person precisely.

Finally, note that one of these hands can be printed in less than 50 hours using off-the-shelf and standard machinery tools that can be found in stores around the world.

Figure 26. Open Bionics robotic hand (33)

4. InMoov Hand

InMoov, published in 2012, is the first life-size open-source humanoid in the world. As explained before, open-source concept is based on sharing and enhancing, so that the robot can be printed entirely by any home 3D printer with a 12 x 12 x 12 cm area. Totally free and fully functional, this robot is within reach of many amateur people.

The designer is Gaël Langevin, a French sculptor who decided to make his robot accessible. All the parts of the robot are located on his creator's site, attached to a non-commercial, attribution license (34).

Furthermore, it is obvious that one of the numerous practical applications of the robot is the creation of functional prostheses. For this purpose, InMoov hand has been constructed in this final project to study how to obtain low-cost prostheses.

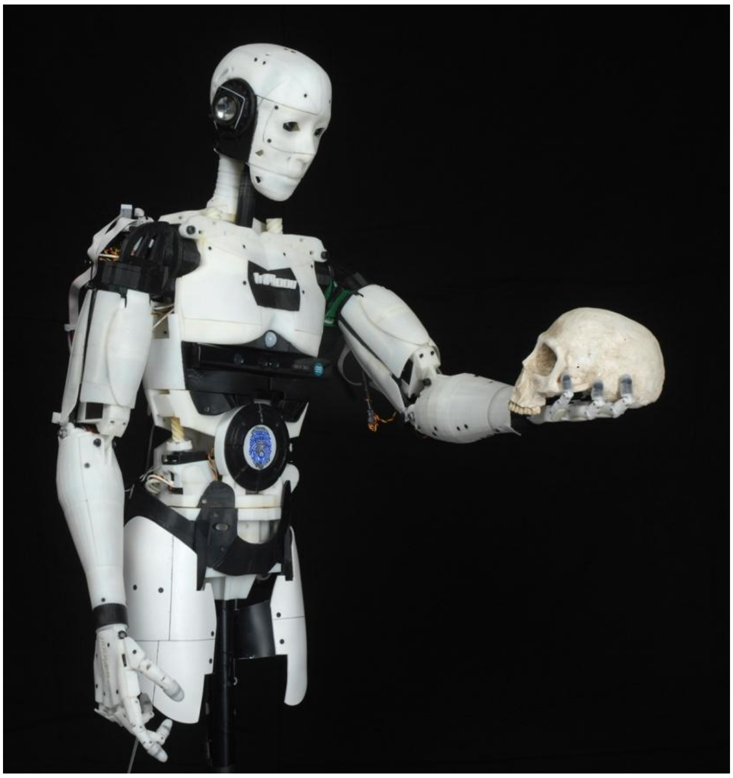


Figure 27. InMoov humanoid (34)

4.1. Hand description

InMoov hand is anthropomorphic having five fingers with human configuration (the thumb is opposable).

Besides, taking into account the objectives of the project, printing also the forearm has been decided to facilitate the accommodation of the servomotors that move the hand.

Size and weight are comparable to those of standard limbs from adults. A comparison between my hand and InMoov hand is shown in Figure 28.

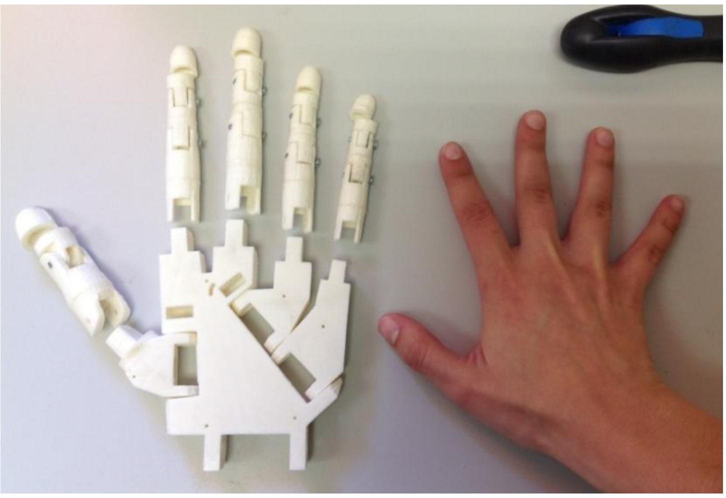


Figure 28. Comparison between my hand and InMoov hand

In this way, the total weight calculated includes both parts: the hand and the arm. This numerical value is equal to 0,722 kg.

Regarding the total size, Table 1, 2 and 3 display the centimeters in all three axes of each part (forearm, hand and fingers).

FOREARM	Total	Smaller part	Bigger part
Length	27,6	X	
Width	X	6,4	10,9
Thickness		4,3	19,1
Perimeter		17,4	33,2

Table 1. Forearm dimensions (cm)

HAND	Palm	Wrist
Length	8,6	2,9
Width	9,3	5,4
Thickness	2,7	2,7

Table 2. Hand dimensions (cm)

FINGERS	Thumb		Index finger		Middle finger		Ring finger		Little finger	
Length	7,9		9,5		10		9,5		8,3	
	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down
Width	1,7	2	1,5	1,8	1,5	1,8	1,3	1,6	1,2	1,5
Thickness	1,6	1,9	1,4	1,7	1,4	1,7	1,2	1,5	1,1	1,4
Perimeter	4,6	6,7	4,4	6,5	4,4	6,5	4,1	6,2	4	6,1

Table 3. Fingers dimensions (cm)

As for degrees of freedom, the hand has 15 DOFs. Each finger, except for the thumb, has 3 DOFs (three different joints). The thumb has 2 DOFs, and the remaining DOF is due to the rotational wrist. The compromise with simplicity and low cost led us to choose this design of a hand with 15 DOFs even affecting the complexity and versatility of the robot.

The hand is underactuated since it uses six actuators to move fifteen degrees of freedom (less actuators than DOFs). Each one of the five servomotors from the forearm moves one single finger individually. So, some actuators move more than one DOF.

The transmission of movement in the system is due to the synergistic actuation of servomotors and tendons as it will be explained in the next section which details the construction procedure.

4.2. Fabrication and assembly process

In order to carry out printing and construction of the robotic hand (mechanical part), several steps have been previously fixed to work in an organized and efficient way:

1. Adapting a workplace with all necessary tools and listing the needed materials.
2. Printing in three dimensions all the parts of the project and assembling them.
3. Coupling servomotors to the robot.
4. Inserting and tightening the tendons.

Every step will be detailed so that the manufacturing process can be understood as a whole.

4.2.1. Workplace and materials

The workplace has been the laboratory of the “Department of Systems Engineering and Automation of Carlos III University of Madrid”. A room of the department has been enabled for my co-worker and me in order to develop this project. This site, plus enough space for work, contained a 3D printer, *P3Steel* model, having FDM technology; various portable and desktop computers, and other common tools present in laboratories and workshops of the university (screwdrivers, pliers, nails...). The most important material has been ABS plastic[1], which has been used to print all the pieces.

The software used to control the 3D printer has been *Repetier Host*, which instructs the printer how the pieces should be: their measurements and other settings. The programs utilized to generate commands for the 3D printer have been *Slic3r* and *Skeinforge*, considered pure slicer software. They are all free software.

Finally, adjusting the parameters of all the pieces from InMoov site (35) and the mechanical calibration of the printer have been required to start printing the hand and the arm. The files have .stl extension, the standard data transmission format for rapid prototyping industry. This format creates 3D models through triangles of different sizes.

The parameters which should be taken into account to obtain a high-quality piece in a moderate time have been:

- Percentage of infill: determines the amount of plastic to fill the piece.
- Layers thickness: the width of the first layer is usually different from the rest.
- Fill pattern: the most common are squared and hexagonal patterns.
- Printing speed: depends mainly on the extruder temperature, the type of filament and the quality of the printer.
- Skirt: additional extruded plastic before starting the printing.
- Brim: additional thickness of the first layer to achieve a better adhesion to the bed.
- Supports: special structure to support overhang pieces.

4.2.2. Printing and assembly processes

The process of printing has been performed by analyzing physically and mechanically the pieces to deduce whether they would be able to support the effort to be undergone.

[1] See Annex C: Datasheets. 1. ABS plastic

The order of printing has been the hand, the wrist and, finally, the forearm. Next figures show representative printed pieces and the 3D printer working:

Figure 29. A complete finger

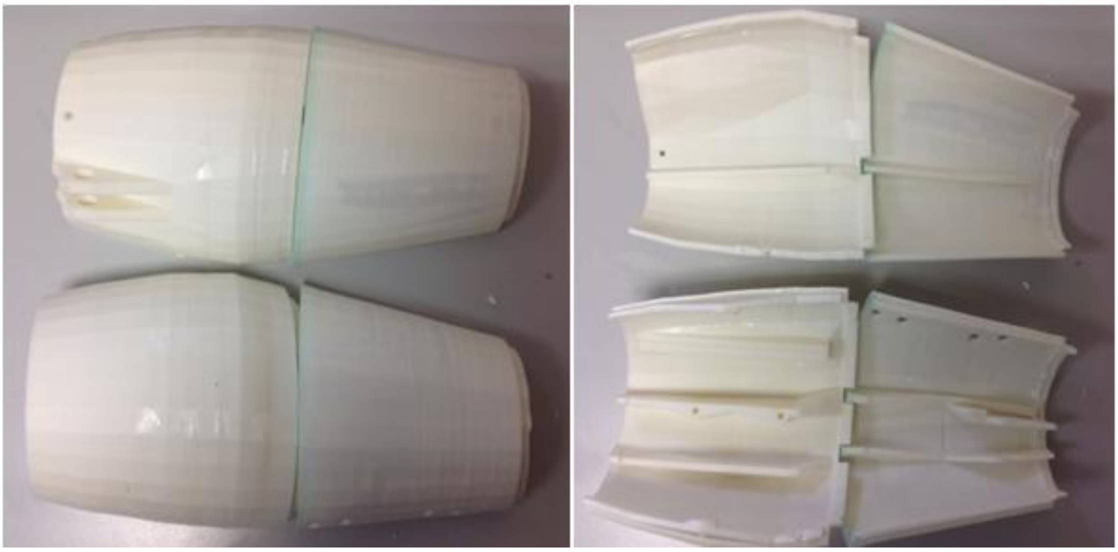


Figure 30. The forearm

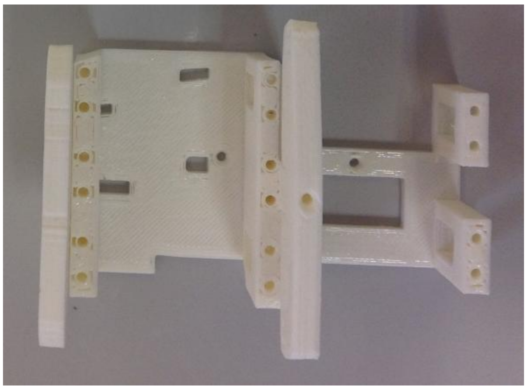


Figure 31. Servo bed

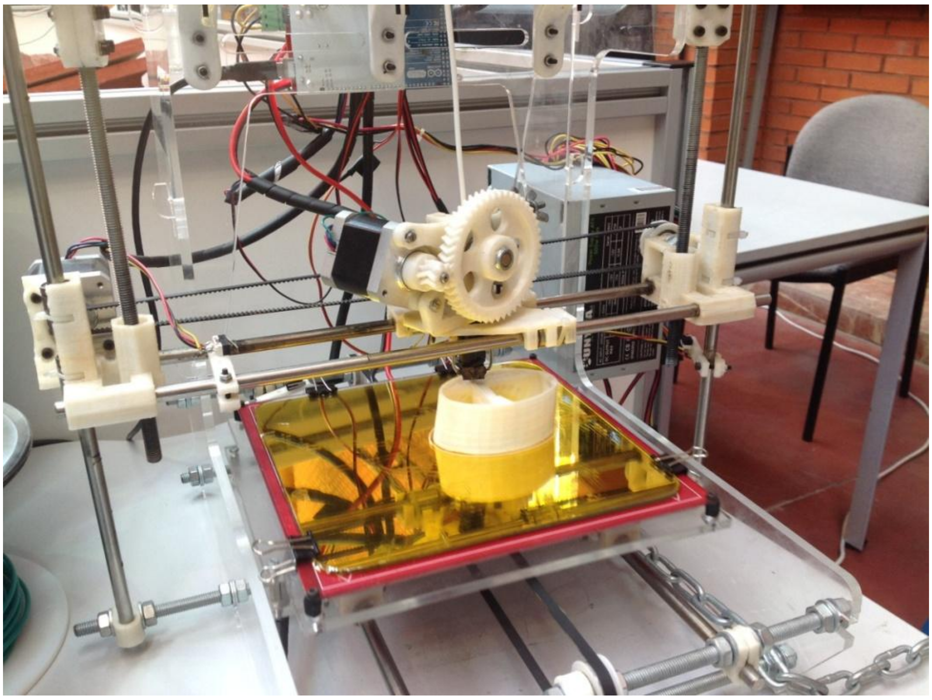


Figure 32. The 3D printer working

It is noteworthy that all the pieces have needed a preprocessing procedure in order to adjust holes tolerances, smooth the surfaces to be glued and strengthen the weakest parts.

After printing, joining and fastening processes have been carried out. The needed tools for this purpose have been: screws, washers and a mixture of ABS plastic and 99% acetone. This mixture ensures that plastic parts melt and join in a resistant way. As a sample, Figure 33 shows screwed parts and glued parts of a finger, and the mixture used to paste them.

Figure 33. Finger and the mixture of ABS plastic and 99% acetone

Then, following rigorously the instructions (35), the hand and forearm have been assembled by solving doubtful steps by intuition, spatial vision and logic based on the knowledge of physics, robotics and mechanics.

Finally, the process with a number of significant photographs is shown in Figure 34.

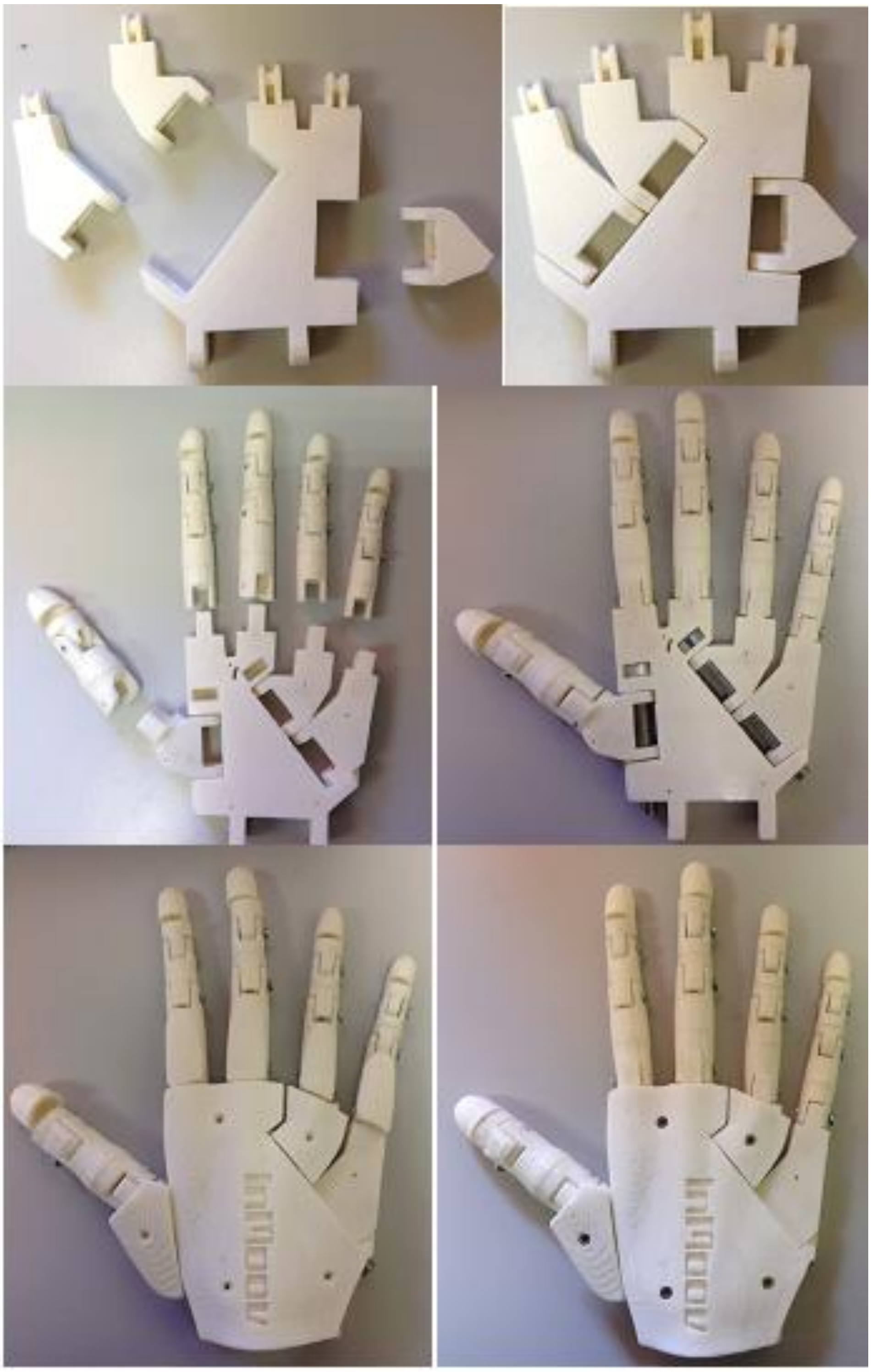


Figure 34. Assembly process

4.2.3. Coupling of servomotors

Servomotors are self-contained electric devices that rotate or push parts of a machine with great precision. In this project, the rotation mechanism tenses and loosens the tendons in such a way that the fingers flex or extend.

There have been placed six actuators or servomotors. Each servomotor (except for the sixth one) has been slightly manipulated to facilitate the introduction of tendons. A small pulley has been coupled in each servomotor as it is illustrated in Figure 35:

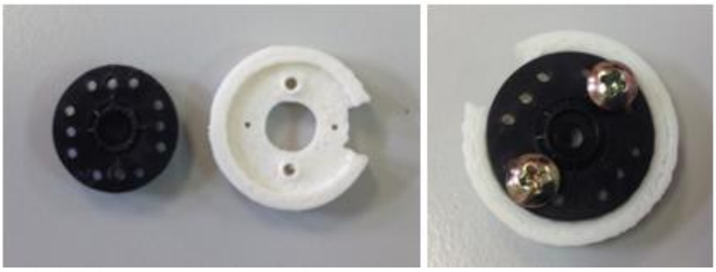


Figure 35. Pulley

As already mentioned above, the principal function of the forearm has been enclosing the actuators that move the fingers. Thus, the six servomotors haven been placed in the following position: five on the forearm and one on the rotational wrist. In order to fix servomotors in the right place, little screws have been used.

To maximize the space destined to servomotors on the forearm, three of them have been placed together and, below them, the remaining two. Besides, the first three servomotors have been put in opposite directions to facilitate the rotation of all of them. This fact can be observed in Figure 36 showing the final result after coupling the five servomotors.

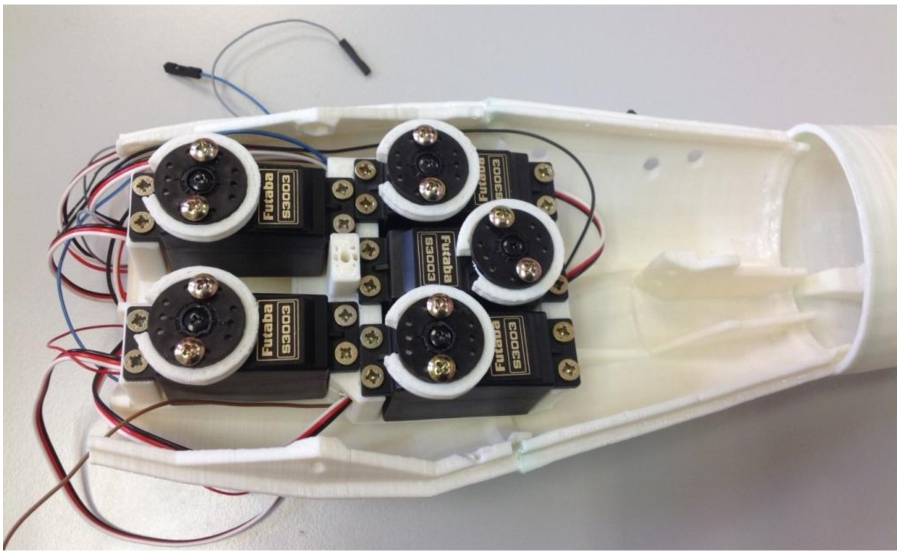


Figure 36. Final coupling of servomotors

On the other hand, the motor from the wrist has been coupled directly, since there are no tendons in this part. So, its rotation causes the movement in the whole wrist. To do so, a printed gear has been coupled to the servomotor to properly transfer the motion.

Figure 37. Servomotor with the gear

4.2.4. Insertion of tendons

Finally, as the last step of the mechanical part, tendons have been inserted into the hand and the forearm through the wrist. The material coupling the motion of the actuators to that of the fingers has been nylon fishing line.

The procedure has consisted of inserting a couple of fishing lines through each finger. One line serves to extend the finger and the other one, to flex it. The pieces have been prepared with holes determining the path the thread had to follow. So, with the help of pliers, tendons have been tightened through the hand and wrist.

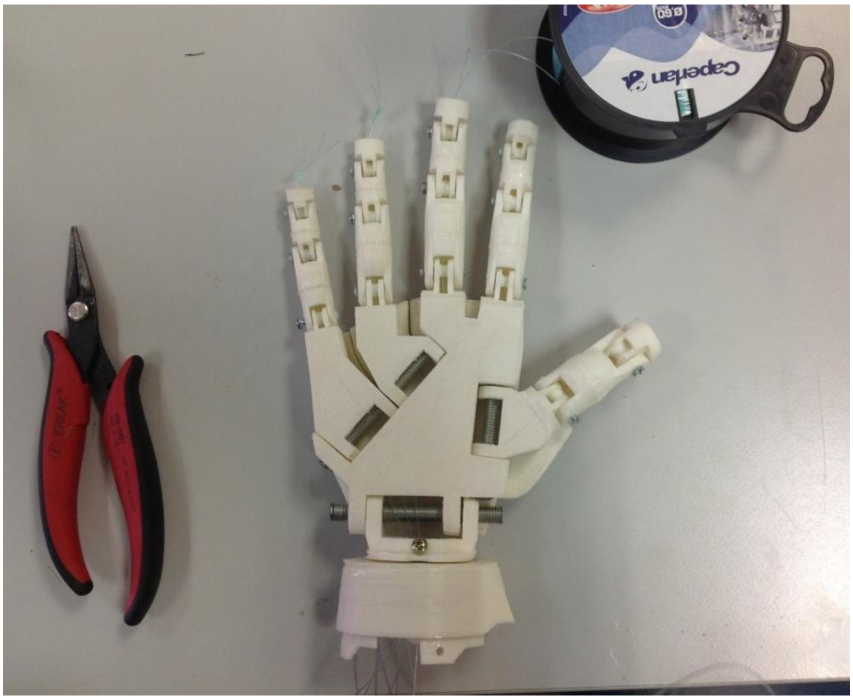


Figure 38. Insertion of tendons with pliers

Then, fishing lines must be properly introduced into the distributor of tendons located in the forearm. In this manner, lines have reached servomotors, the final destination.

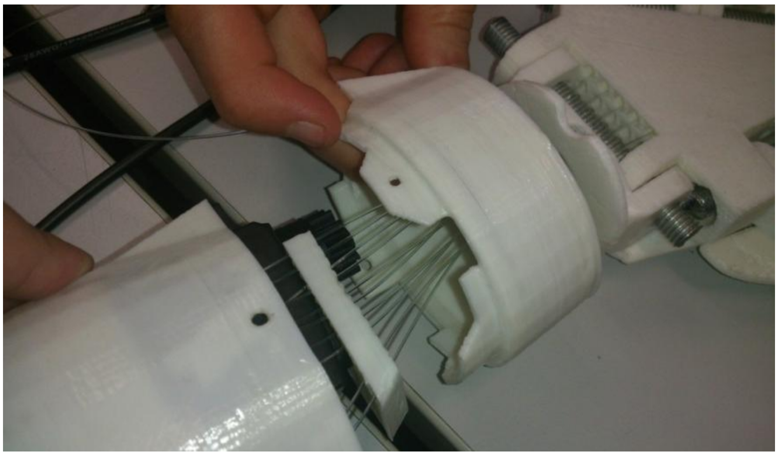


Figure 39. Lines through the distributor of tendons

After performing this task on all fingers, the upper ends of the lines protruding from the fingertips have been attached and secured with contact glue so they could not move. Then, the excess of line has been cut and the tips of the fingers have been finally glued as it can be seen in Figure 40.

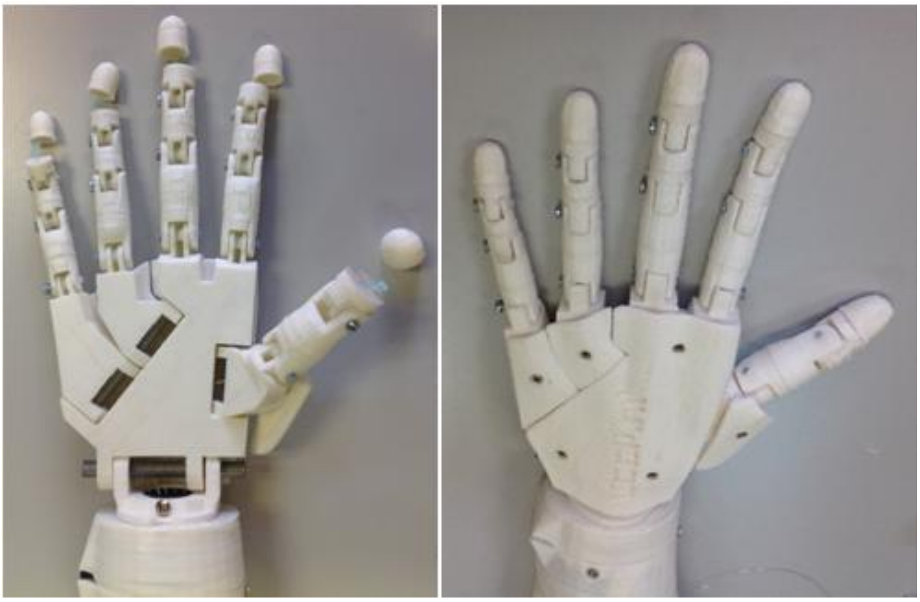


Figure 40. Gluing the tips

Regarding the other ends of each couple of lines, they have been properly placed on the servomotors in such a way that the desired effect (extending and flexing all the fingers) has been achieved. Many experimental tests have been necessary to obtain a successful outcome.

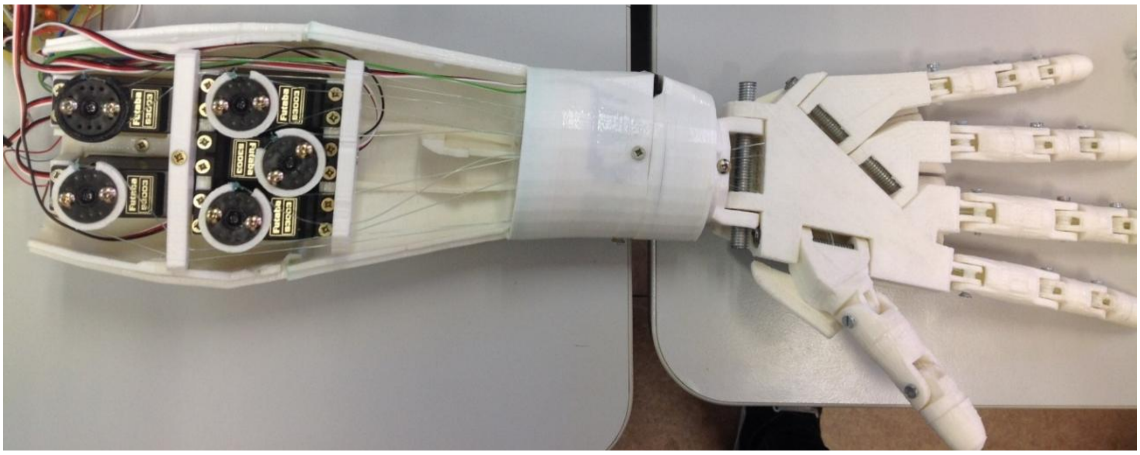


Figure 41. Placing tendons on the servomotors

Finally, the excess of fishing line protruding from the forearm has been cut after stretching it sufficiently.

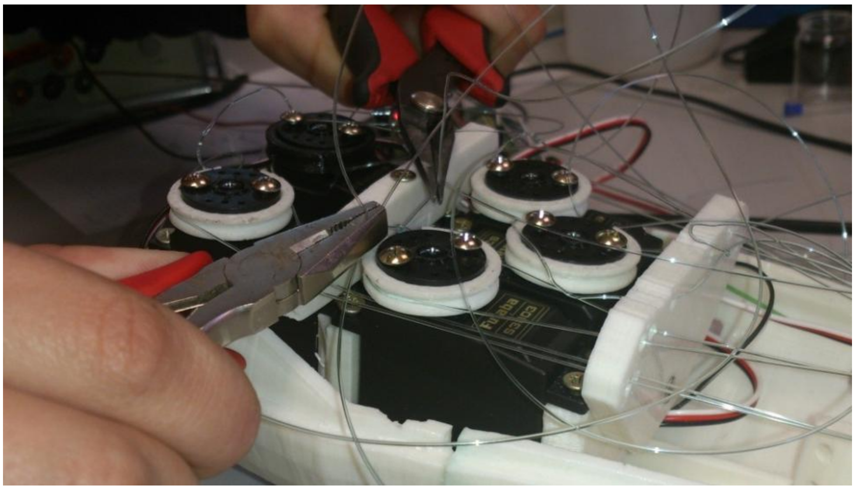


Figure 42. Stretching the lines to cut

Figure 43. Final result of the coupling between tendons and servomotors

The missing part of the forearm has been put to cover the entire mechanism of the servomotors. The arm had to be completely closed and the access to the actuators restricted to prevent human errors in this area.

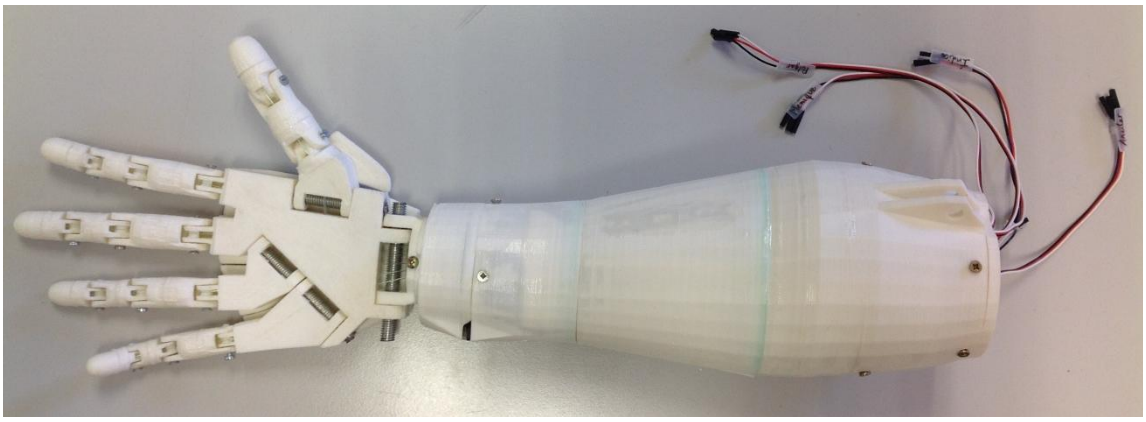


Figure 44. Closed forearm after coupling tendons and servomotors

A cover has been also put on the spherical gap remaining because of the cylindrical forearm. By the holes provided for this function, only wires from servomotors can pass through this cover. These cables need to be connected to the power source from the outside. Furthermore, in order to avoid confusion between the wires since the forearm is entirely sealed, little labels identifying the fingers corresponding to the cables of each servomotor have been hooked.

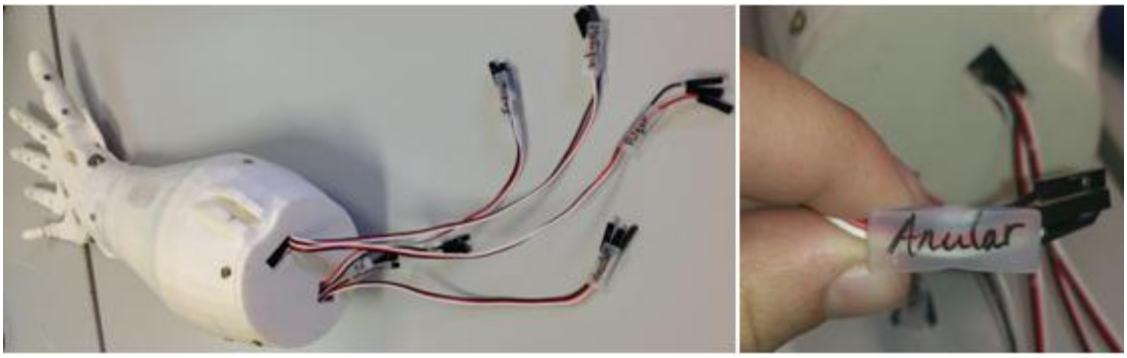


Figure 45. Cables with identifying labels coming out of the cover

4.3. Supply circuit of servomotors

For the movement of each one of the fingers, servomotors have been chosen since they are very simple to control and usually have reduced power consumption. The hand has been designed for holding small objects, so the torque that is required is also small. With these specifications, servomotor Futaba S3003[2], whose main features are present in Table 1, has been selected.

Volts	Torque	Speed
4.8 V	44 oz-in (3.2 kg-cm)	0.23 sec / 60°
6.0 V	57 oz-in (4.1 kg-cm)	0.19 sec / 60°
Dimensions		**Weight**
1-9/16 x 13/16 x 1-7/16 in (40 x 20 x 36 mm)		1.3 oz (37 g)

Table 4. Servomotor Futaba S3003 features[2]

[2] See Annex C. Datasheets. 2. Servomotor Futaba S3003

Servomotor Futaba S3003 is mainly formed by a DC motor, a gearbox and a control circuit. A figure of the dimensions (in millimeters) of this model of motor is shown below.

Figure 46. Dimensions of Servomotor Futaba S3003[3]

These actuators chosen for the movement of the fingers make use of pulse-width modulation (PWM) to bring the DC motors to specific angular positions.

Servos need to be fed through an external power supply due to the inability of the microcontroller to provide all the power needed to move all engines. A constant voltage of 6 V is required to supply the actuators. This voltage must be independent of variations in the current flowing through the load and must not show any ripple. For this reason, a voltage regulator has been also necessary.

The function of the voltage regulator used is providing a specific and stable energy to feed the actuators from a 12 V battery input, and proffering more power to the servomotors. A three-terminal fixed voltage regulator has been chosen because they

[3] See Annex C. Datasheets. 2. Servomotor Futaba S3003

have a terminal for unregulated input (IN), regulated output (OUT) and ground (GND), and are set to provide a constant output voltage like ± 15V or ± 6V.

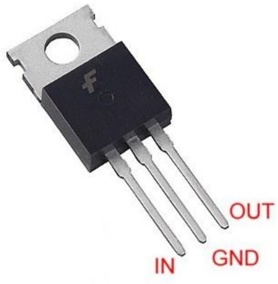


Figure 47. Three-terminal fixed voltage regulator

Within this type of regulators, they are found the µA 78XX (positive) and µA79XX (negative) Fairchild series. The last two digits (XX) indicate the output voltage and may be 05, 06, 08, 12 or 15 (V). The model that meets all the needs of the proposed project is the µA 7806[4]. Table 2 displays its main features:

Output voltage	6V
Operation temperature	0-125ºC
Maximum output electric current	1A

Table 5. µA 7806 voltage regulator features

Figure 48 describes the fixed voltage regulator circuit used, the µA7806, to obtain a fixed voltage of + 6V. Capacitors C1 and C2 improve the transient response of the regulator.

[4] See Annex C. 3. Voltage regulator µA 7806

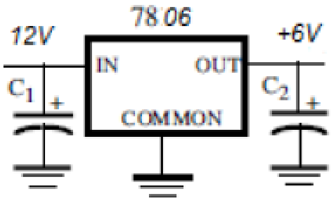


Figure 48. µA 7806 voltage regulator scheme

To implement the regulator, an interface board to be connected to the microprocessor has been designed. In the board, apart from the regulator, the connectors for the servomotors and feeding connections are included.

For the design of the interface board, OrCAD software has been chosen. This specialized software for the design of electronic circuits, is divided into four main applications that enable performing the following operations:

- CAPTURE: description of the design which can be accomplished by electrical scheme or with the hardware description language VHDL.
- PSPICE: simulation of analog, digital and mixed circuits (analog plus digital circuits).
- LAYOUT: performing of printed circuit boards.
- EXPRESS/CAPTURE: design of digital circuits with programmable, logic devices and memories.

The application that interests us for the implementation of the interface board has been LAYOUT, that allows the design of the PCB (Printed Circuit Board). This is the interface board that has been finally designed:

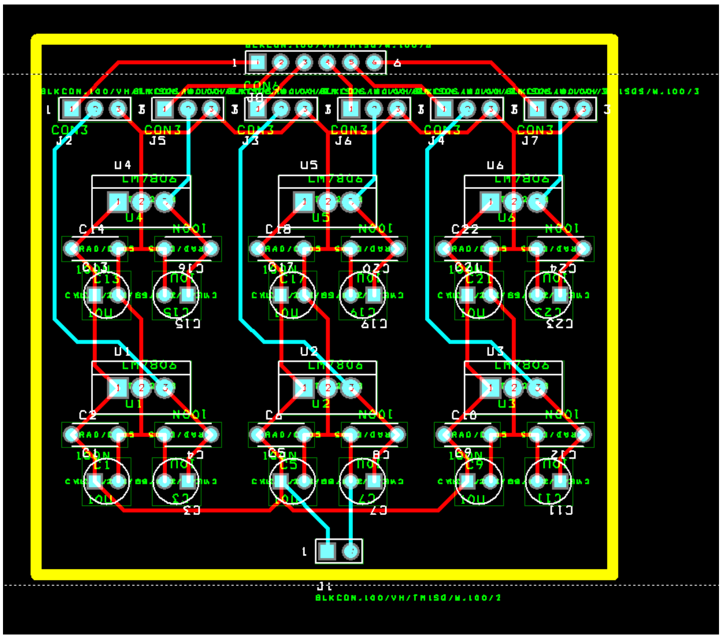


Figure 49. Interface board design

Then, the university services have been requested to manufacture the PCB to cut costs. Finally, the necessary components have been manually welded by us.

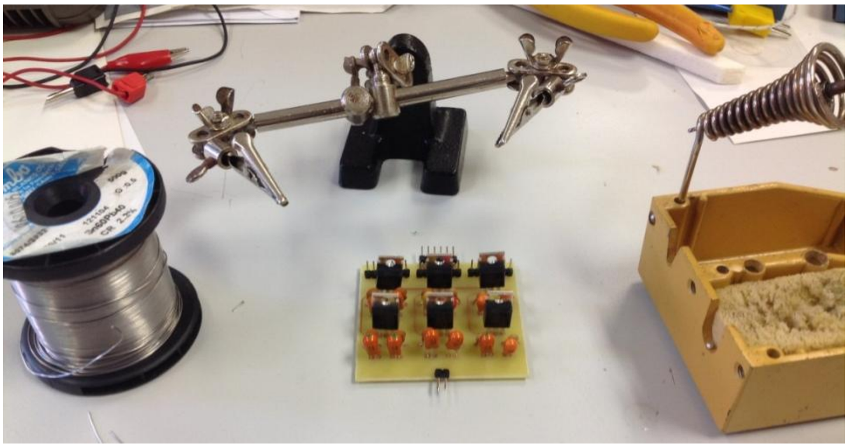


Figure 50. Working place to solder the components

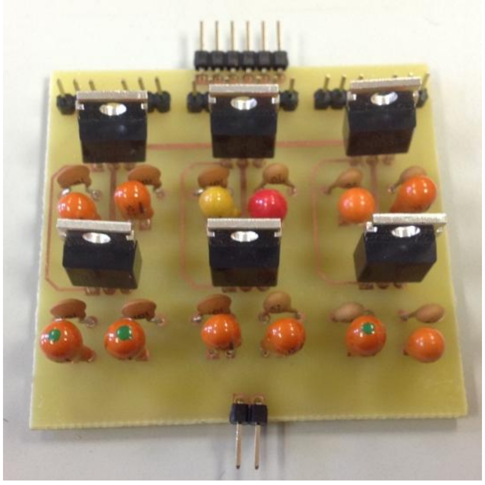


Figure 51. Fabricated PCB

5. Control of the robotic hand

In this part, the control implemented in Simulink for our printed robotic hand is described. The main features of the microcontroller chosen for this purpose and how the signal PWM is generated, necessary for the proper functioning of servomotors, will be also addressed.

The microcontroller performs two tasks. On the one hand, it has to communicate with the PC and therefore must be able to receive the data that the computer sends it. Its other task is to generate the PWM waves that drive the servomotors according to control commands received by the PC.

The microcontroller receives commands which are programmed in Simulink. In this environment, the programming is executed graphically by a block diagram. Simulink software provides elements windows for programming, and components that are linked to reading and data collection. Using this software, block diagrams can be configured for different types of applications. Each block has its proper internal programming.

The microcontroller used is STM32F4-Discovery. This model has been chosen because of its high-end performance, its low cost and its good compatibility with Simulink environment. The following section will be dedicated to this microcontroller in more detail.

5.1. SSTM32F4 Microcontroller

The STM32 series is developed by STMicroelectronics. It is a family of microcontrollers based on ARM cores of 32-bits of ARM Holdings. Some of these nuclei are Cortex-M4F, Cortex-M3, Cortex-M0 and Cortex-M0 +. The STM32F4 series is versatile, easy to use, low-cost, and is the first one based on ARM Cortex-M4F.

The ARM architecture is the acronym for Advanced RISC Machine. The architecture RISC (Reduced Instruction Set Computer) is a type of CPU design that is generally used in microcontrollers. Some of its characteristics are presented hereafter: they have fixed size instructions (displayed in a reduced number of formats), they have many general purpose registers, they execute instructions in parallel and they reduce memory accesses.

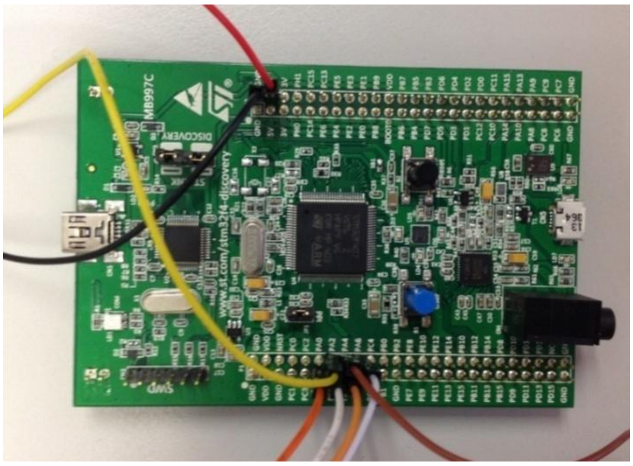


Figure 52. STM32F4-Discovery Board (ST Microelectronics)

The main features of the STM32F4-Discovery board are cited here:

- Core ARM Cortex-M4F at a maximum clock speed of 180 MHz.
- 192 KB of static RAM, 64KB of CCM (Core Coupled Memory), 4 KB backup memory, 80 bytes of backup memory with tamper detection.
- STM32F407VGT6 Microcontroller with 1MB of flash memory, which has 512/1024/2048 KB of general use, 30 KB of boot system, 512 bytes One Time Programmable and 16 bytes of options. LQFP100 encapsulated.
- Power supply: via the USB bus or from an external power supply of 5 V.
- ST MEMS LIS302DL motion sensor, accelerometer with 3-axis digital output.
- ST MEMS MP45DT02 audio sensor, digital omnidirectional microphone.
- Eight LEDs.
- Two buttons (user and reset).

- USB OTG FS with micro-AB connector.
- 80 pins of general purpose.
- 16 DMA: Direct Memory Access channels.
- 6 USART: Universal Synchronous Asynchronous Receiver/Transmitter.
- 3 SPI: serial data protocol used by microcontrollers to communicate with one or more peripheral devices quickly over short distances, or for communication between two microcontrollers.
- 3 I2C: a serial communications bus. Its name comes from Inter-Integrated Circuit. Used in industry mainly to communicate microcontrollers and its embedded systems, and to communicate with each other embedded circuits hosted on the same printed circuit board.
- 3ADC: analog-digital converter.
- 2 DAC: digital-analog converter.
- RTC: real time clock, multiple timers.
- CRC unit: Cyclic Redundancy Check.
- Ethernet.
- 2 independent watchdogs: electronic timer, whose operation is detecting failures and recovering from them.

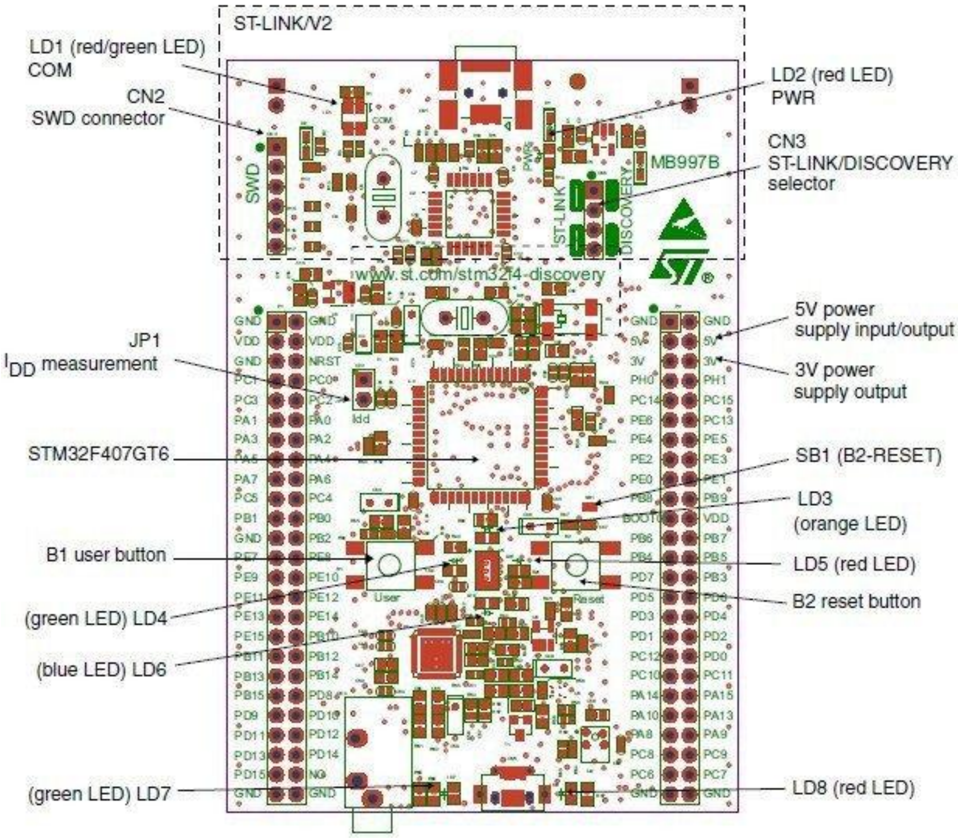


Figure 53. Components and pins description (36)

5.2. Rapid control prototyping programming methodology through Simulink

A rapid prototyping system for control, designed with Matlab/Simulink by Mr. Antonio Flores Caballero (member from the Department of Systems Engineering and Automation of the Carlos III University of Madrid), has been applied in this project. This system has been part of his doctoral thesis. To better understand the concept of rapid control system, part of this thesis will be quoted:

"The concept of Rapid Control Prototyping (RCP) refers to all software and hardware techniques needed to shorten development and implementation times of control systems, making use of a high level of abstraction in programming. The high level of abstraction is obtained by using graphics-based languages, allowing the programmer to transfer ideas to the computer in a more natural way, avoiding all aspects of low-level configuration of the hardware system, because these steps are performed automatically.

Using a high level of abstraction in programming, by means of graphics-based languages, has advantages even for experts in textual programming. Utilizing a language of this kind makes available the use of real control hardware to a multidisciplinary audience. It also allows that the aforementioned controller behaves exactly as its behavior was defined in its graphic language of programming.

This last point would not be possible if it was necessary to perform a manual transcription from the graphic language to a textual language, since the programmer would introduce modifications inadvertently. These high-level languages of abstraction are available in software environments based on the Model Based Design. With the same graphical language, simulations of electromechanical systems, systems identification based on catch data or programming RCP systems among many other tasks, can be performed" (37).

Using this RCP methodology in the project is an advantage since a previous work of the department has been reutilized. Another advantage of using this type of programming in Simulink to implement the low-level control of the hand, is the easy integration with posterior high-level control with EMG signals. That is, the capture and analysis of EMG signals (with the same microcontroller) as well as the control implementation by using machine learning techniques, have been carried out using Matlab/Simulink because of the tools offered by this program in these fields. Therefore, it makes sense that the implementation of low-level control of the robot hand is developed in the same environment and the same methodology, in order to make integration as straightforward as possible.

5.3. Control models

In order to perform the correct control of actuators with STM32F4-Discovery microcontroller, two designs based on complementary models in Simulink have been developed. A host model, which is executed on a computer, and a second model, that is programmed into the microcontroller (target model). Significantly, one of the advantages of the control system used is that the microcontroller is programmed using Simulink block diagrams. These blocks are then loaded into the aforementioned microcontroller, which is not possible with commonly used textual languages such as C or C ++.

To develop both control models has been needed to add libraries "WAIJUNG BLOCKSET" to the library browser in Simulink. These libraries have been developed by Aimagin and supplemented by "UC3M ADDONS STM32F4", created by Mr. Antonio Flores Caballero.

In the following points are described in greater detail both models used to control the movements of the motors.

5.3.1. Target model

This model has been programmed into the microcontroller. As mentioned before, it is based on Simulink block diagrams and some blocks will be described thereupon.

The first block inserted has been Target Setup, which is within the Waijung Blockset library, developed specifically for these microcontrollers. This block has been utilized to configure the type of controller (STM32F407VG) and compiler (GNU ARM) to be used in the Simulink model. In Figure 54 is shown this data and the sample time (0.01 sec) among other adjusted parameters.

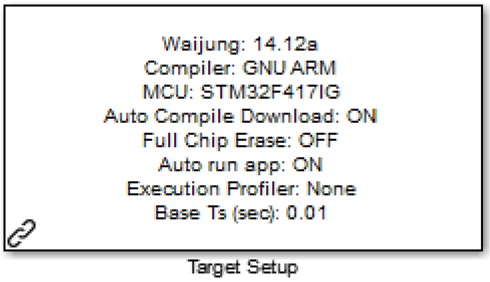


Figure 54. Target Setup block

The next block placed on the model has been the USB VCP Receiver STM32F4 block (Figure 55) to receive data sent from the PC to the controller. This block is within the library UC3M ADDONS STM32F4.

Parameters such as the type of signals, the sampling time and the header and terminator of messages to be received by the microcontroller, have been defined. This is important to achieve a good communication between PC and microcontroller.

A number of six single signals (signals for controlling each actuator) has been fixed. These six outgoing signals correspond to the angular positions to which servomotors should rotate.

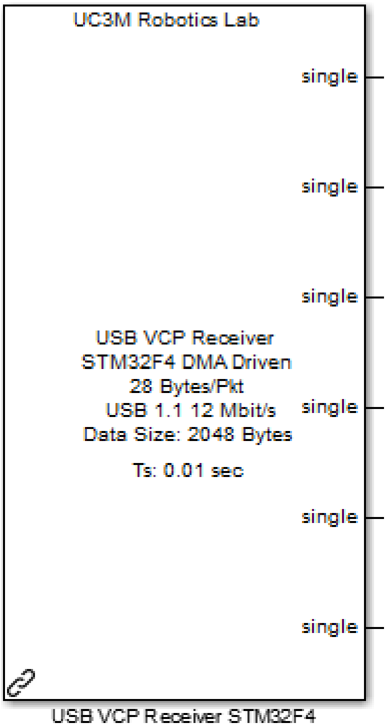


Figure 55. USB VCP Receiver STM32F4 block

The outgoing signals from the previous block have been also configured. For this purpose, first, Memory block has been placed on the model to initialize the values of the signals controlling the servomotors. These initial conditions define the starting angular positions of the actuators.

The following step has been determining the range of values corresponding to pulse width of PWM control signals, to which servomotors rotate from 0 ° to 180 °. To that end, angular positions have been introduced and then a function has mapped the angular values received by the controller, to obtain pulse width values for PWM control signals. Thus, more intuitive control of the turn of servomotors is achieved.

The numerical values introduced into the function have been calculated experimentally. In the equation, the parameter "u" is the input signal, i.e., the angular position to which motors have to be rotated. Experimentally, a pulse width of 2.3 has been obtained for position 0 °. Similarly, a pulse width of 11.3 corresponding to the angular position 180°

has been obtained. These tests have given rise to the expression that transforms the angular positions on corresponding pulse width values: 2.3 + 4.5 / 90 * u.

Then, another block called Saturation has been chosen to limit the input signal to the range enclosed by maximum and minimum values of pulse width obtained in experimental tests. This fact prevents the signal from entering the block with exceeded values and producing a malfunction.

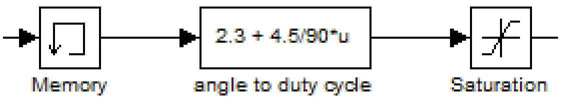


Figure 56. Saturation block

The last block located on this model is in charge of generating six PWM control signals with the pulse width values received at their inputs. Its name is UC3M Basic PWM and is also included in the library UC3M ADDONS STM32F4. Three blocks of this type with two outputs each one, have been necessary for this project.

The parameters defined in these blocks have been the period of PWM signals generated, the sampling time and the ports through which signals are generated.

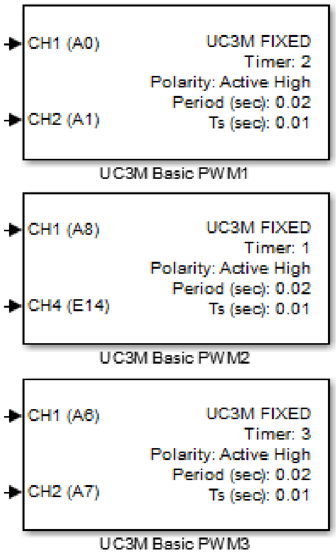
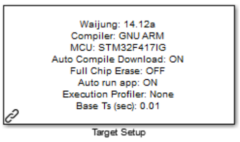


Figure 57. UC3M Basic PWM blocks

The whole control model having the blocks properly connected (Figure 58), generates six PWM signals from the values sent to the microcontroller from a PC.



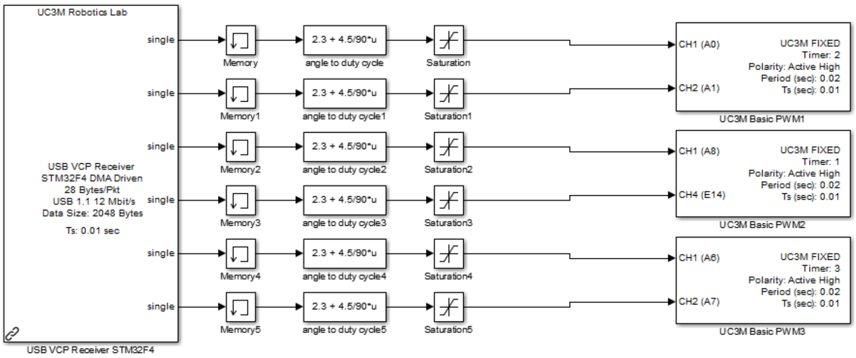


Figure 58. Target Model

5.3.2. Host model

The first block put in the model has been Host Serial Setup, used to select the COM port of the computer through which data have been transmitted to the microcontroller, and the communication speed. It should be noted that the maximum speed allowed by the microcontroller is 12 Mbps.

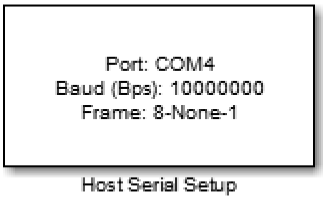


Figure 59. Host Serial Setup Block

To control the angle of rotation of the servomotors, a Slider Gain block has been selected. This block is a slider gain which multiplies by a scalar whose value can be varied with a slider. In this particular model, the input block has had a value of 1 to be multiplied by a variable gain corresponding to the angular control signal of the hand servomotors. The lower and upper limits have been defined to 0 and 180 for the slider gain range.

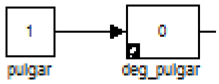


Figure 60. Slider Gain Block

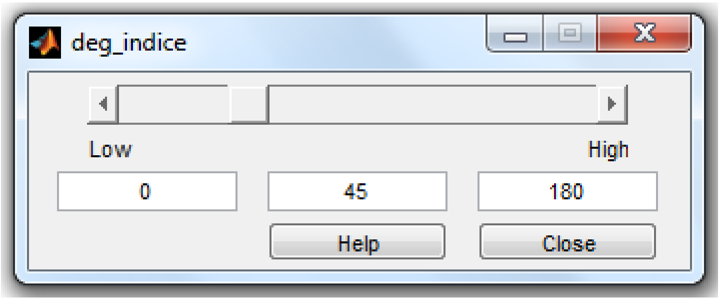


Figure 61.Slider Gain block

Lastly, transmitting data through the COM port from the computer to the microcontroller has been necessary. For that purpose, Host Serial Tx block (within Waijung Blockset) has been selected. The configuration of this block is mainly related with the selection of the COM port, the code relaying the information (binary, ASCII), the header and terminator of messages and the number and type of data transmitted.

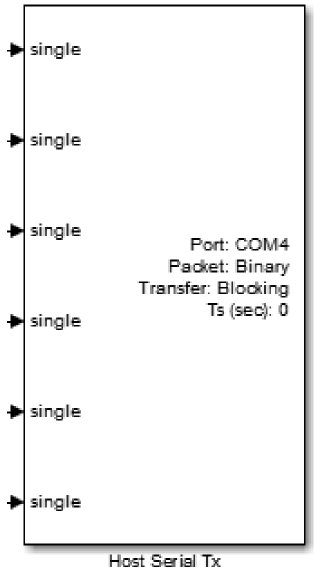


Figure 62. Host Serial Tx block

The running time for this host model must be infinite since the stop should be manual. By connecting all blocks, the completed model has been obtained to send data from the PC to the microprocessor, which converts this information into suitable PWM signals for the control of servomotors (38).

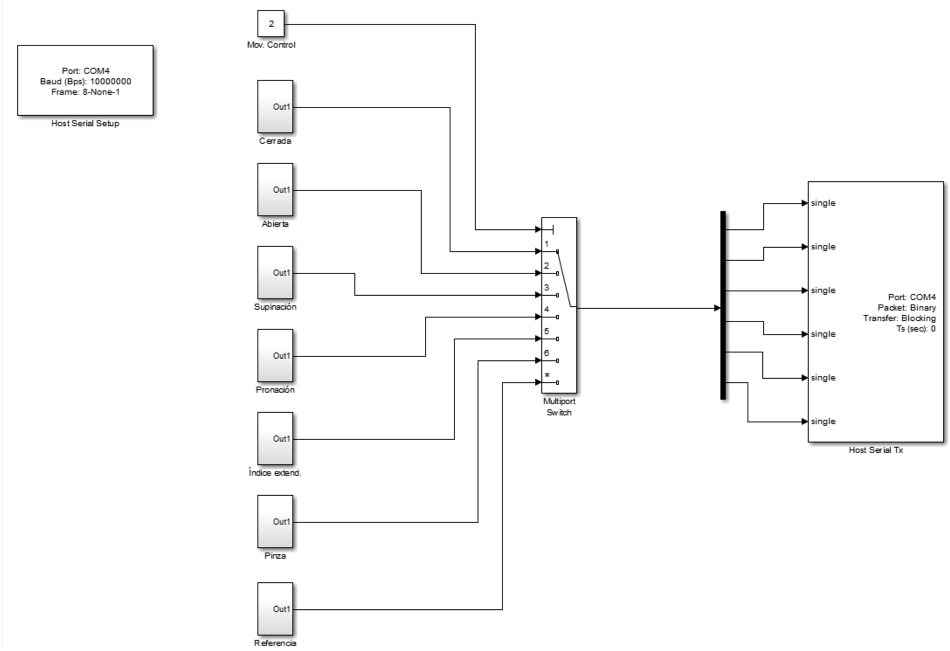


Figure 63. Host model

5.3.3. Implementation of a gestural myoelectric control system

This section focuses on the target and host control models integrated to the neural network.

Table 3 displays the experimental values needed to perform the movements. They corresponds to degrees of rotation and, because of this, all the values fluctuate between 0 and 180 (º). Differences between values from different actuators for similar positions are due to many factors to be taken into account such as the order in which the fingers should move (more rotation usually means more needed time) or the fact that the orientation and distance of the motors is not the same for all of them. In addition, not all the motors need to be at maximum or minimum allowed values to achieve maximum or minimum possible movements for the corresponding part of the hand.

Each actuator has been called according to the corresponding part of the hand that moves. So, "thumb" refers to the motor controlling the thumb and so on. When a movement is selected manually in Simulink, all the motors (or only one in case of supination and pronation) start to rotate to the position fixed by the model. These movements are programmed within blocks that being activated (activated with 1 and deactivated with 0), make the robotic hand reproduces the correct positions.

Movements:	Reference	Open	Closed	Supination	Pronation	Index	Tweezers
Thumb	60	20	150	-	-	150	150
Index finger	65	45	180	-	-	55	180
Middle finger	65	52	150	-	-	160	33
Ring finger	85	8	170	-	-	170	0
Little finger	70	25	175	-	-	175	35
Wrist	180	180	180	0	180	180	180

Table 6. Angular positions of motors for seven different movements

Regarding the movements, these seven different positions have been chosen because they are basic and useful to perform the desired operations: mainly pointing and grasping. A brief description and an image of each movement will be addressed.

- Reference: simulation of a natural and relaxed position. The fingers are slightly flexed as it is shown in Figure 64.
- Open: all the fingers are maximally extended.
- Closed: all the fingers are maximally flexed. It is the position for grasping objects as it can be observed in Figure 71.
- Supination: only the wrist rotates to 0º and the rest of the fingers do not move. The palm of the hand is face up.
- Pronation: exactly the opposed to supination. The palm is face down.
- Index: all the fingers except for the index are flexed. The extended index is useful for pointing.
- Tweezers: the index finger and the thumb are flexed to be in contact. The rest of the fingers are extended. This position allows the user to take small objects.

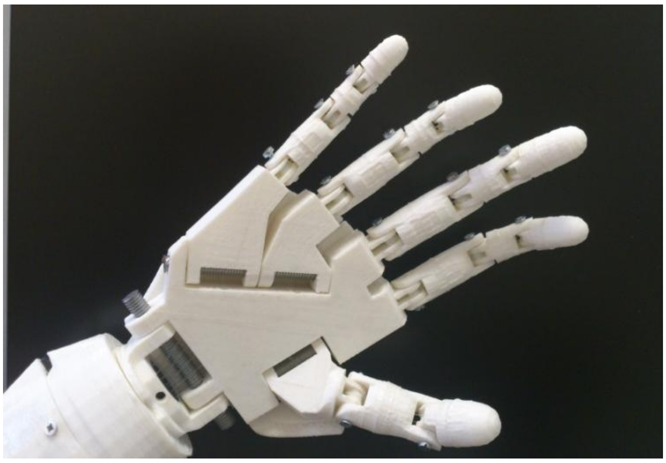


Figure 64. Reference position

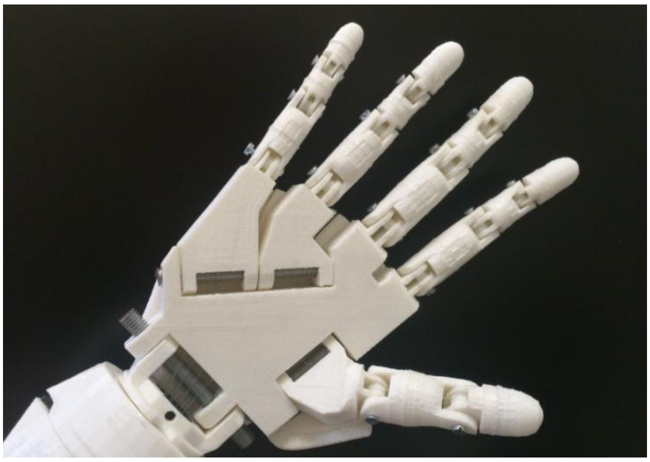


Figure 65. Open position

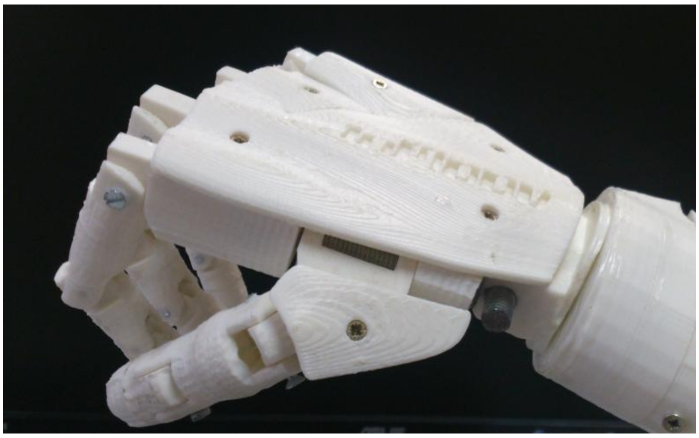


Figure 66. Closed position

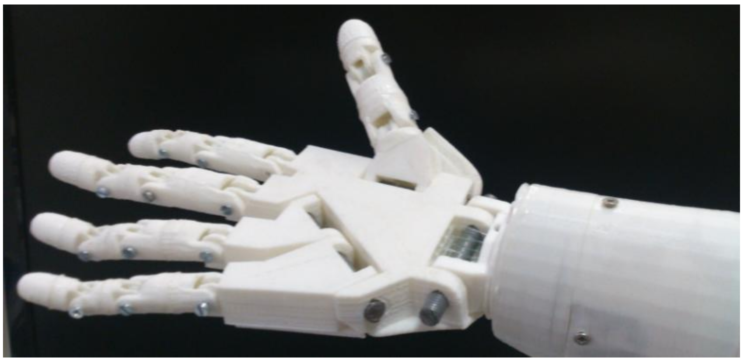


Figure 67. Supination position

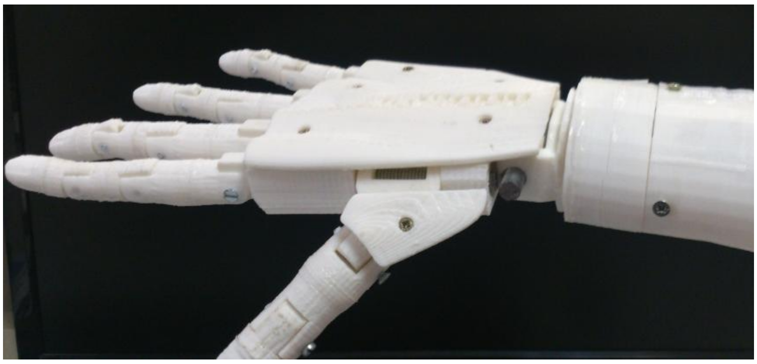


Figure 68. Pronation position

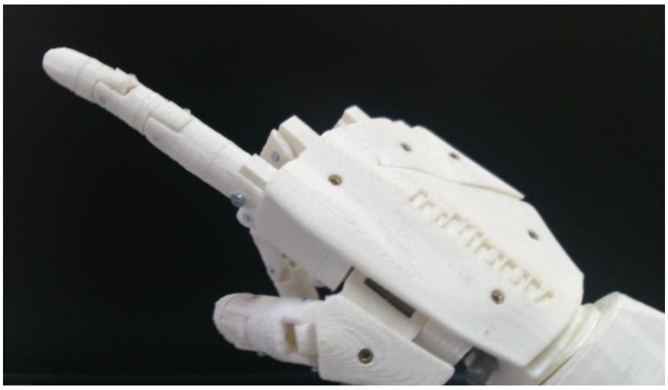


Figure 69. Index position

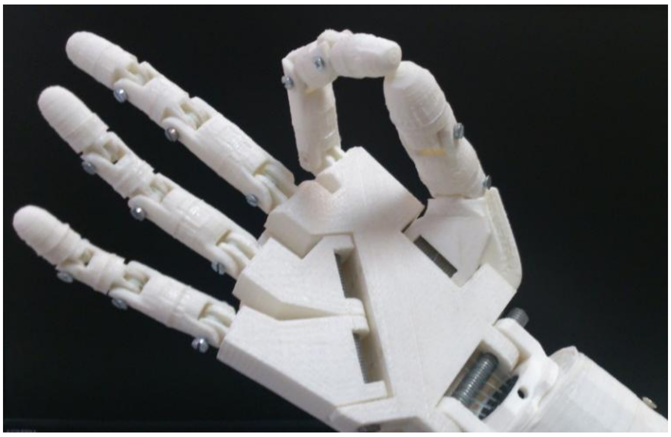


Figure 70. Tweezers position

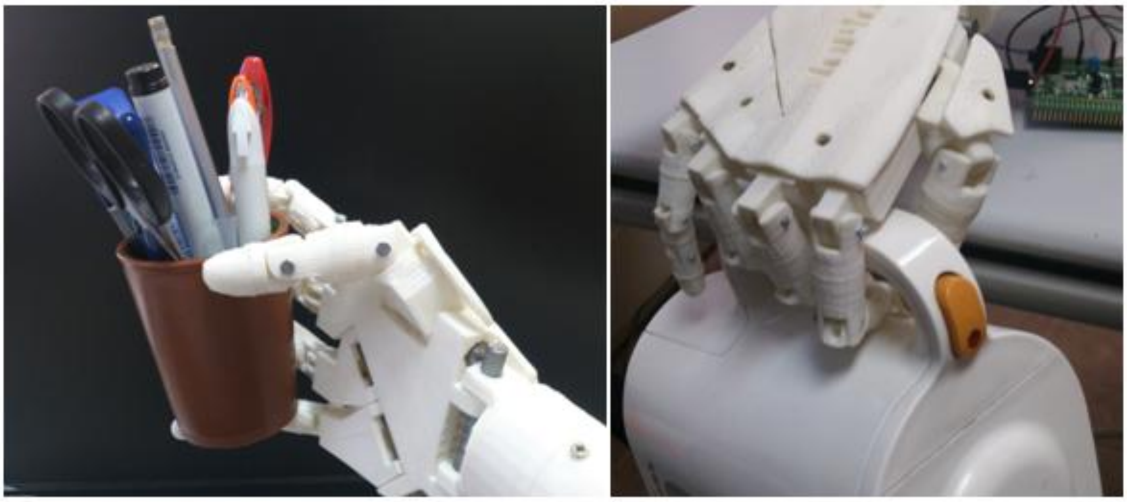


Figure 71. Grasping different objects

To give a brief summary regarding the integration of the implemented low-level control model into the high-level myoelectric control model developed in "Implementation of a neural network-based electromyographic control system for a printed robotic hand" (8). the different preprogrammed grasps are selected depending on the output of a pattern recognition neural network as follows.

The EMG signals are captured and processed, and fed into a neural network trained to recognice a set of different grasps corresponding to those programmed into the robotic hand. Depending on the probabilities output by the neural network, a multiplexer selects which gesture is being performed by the user and activates the corresponding motion block programmed into the low-level controller.

6. Conclusions and future work

In this final chapter, results obtained during the execution of the whole project are analyzed in order to assess whether the objectives have been achieved. Thus, the conclusions to be drawn will also highlight the difficulties found.

It is hoped that this analysis will serve to guide future research in this field in the right direction. For this purpose, some future works are proposed to solve these encountered problems or improve the performance of the device.

6.1. Conclusions

The results have demonstrated the feasibility of the project with all its specifications. However, the most important comments about each part of the job done are going to be highlighted.

First, it is noted that the end result of the work has been the obtention of a low-cost robotic hand having a low-level control system (having a 3D printer and a computer with corresponding software, hand itself costs around 100 €)[5]. As for the required characteristics defined in objectives, it can be claimed that they have been met.

The hand is low-cost even being much more sophisticated than simple cheap hooks. The selected open-source design has allowed the construction of the robotic hand (platform to develop prostheses) in a very cheap manner.

Its configuration and size is anthropomorphic with five fingers counting on the opposable thumb. The entire process can be done with the 3D printer, which makes the end product fully accessible. So, the leap to mass production of prostheses based on this model which is easy to acquire, would be acceptable.

[5] See Annex B: Project Budget

After carefully studying the design of different robotic hands, it has been concluded that the key factor is to optimize the combination of several actuators in the smallest possible space. For this reason, underactuated robotic hands have been the focus to fill this need given the current state of the art of sensors and actuators technology.

So, the minimum number of possible actuators (six: one for each finger and other one for the wrist) has given rise to a moderate weight, which can be supported by a standard amputee with average height. The design chosen in the project can be only used (with modifications) in those amputations in which the forearm is missing (either just below the elbow or above it) due to the fact that actuation system is implemented in the InMoov forearm.

On the other hand, the control system is independent since it can be easily connected or disconnected according to the needs. It provides maximum functionality taking into account the design. So, pointing and grasping positions are achieved (see Figure 69 and Figure 71). The range of objects that the hand has been able to withstand in tests of mobility and grips, as well as the force used for this purpose, are consistent regarding the design.

The tests have shown that the robotic hand has basic manipulation capabilities with a moderated grasping force. The underactuated system with tendons utilized provides flexible grips. It can grasp cylindrical objects like bottles or glasses, and objects with a handle like suitcases or bags, among other things. The printable pulleys which transmit the rotation of the motor to the fingers withstand the continued use of the robotic hand without breaking.

Current robotic systems have not sufficient development in dynamic properties to permit throwing or running, usual human tasks. This fact is due to the actuators, which cannot provide the required energy without making the device too bulky to be used. So, robotic systems should tend to be able to store energy on short-term and to be robust against impacts.

Another specification has been developing the work in a viable and sustainable manner, a criterion that has also been observed using cheap, non-toxic, and even recyclable (such as the ABS, also used for mixing with acetone) materials. The tools used were part of the department; no acquisition of new products with disproportionate price with respect to the usual features of a final degree project has been required.[6]

Besides, the time spent on the project has not been different from standard references (on average, an entire academic year)[7], which proves to be a favorable characteristic for possible mass manufacturing in case of the hand is adjusted to be a prosthesis.

Regarding the motion transmission system, it has been shown that tendons used in this project are suitable and perform their function correctly. They allow all robotic fingers to operate with three degrees of freedom each, except for the thumb, having 2 DOFs. The fingers are able to flex and extend smoothly and at appropriate speed (few milliseconds depending on the movement). However, to achieve these results, multiple ways to insert and knot tendons have been tested for the motors could rotate to given angular positions without stretching too much the threads and avoiding them get away from pulleys. After these experimental tests, it can be concluded that the configuration seen in Figure 43 has reported optimal results.

Furthermore, despite numerous tests of hand movement, tendons have resisted continuous friction and different tensions, so that the material chosen has been a success.

Continuing the mechanical analysis, it can be mentioned that some parts have been broken by continued manipulation to which they have been subjected. This fact had to be solved by reprinting and reinforcing the postprocessing phase. Another related mechanical error has occurred during assembly of the wrist. There was too width and the final configuration was not stable, so addition of extra parts has been necessary.

[6] See Annex B: Project Budget
[7] See Annex A: Stages of the work

After analyzing the compliance of the specific objectives in the construction of the hand, the control phase is going to be examined. Using a graphical programming system based on Matlab/Simulink has allowed the creation of simple specific software compared to classical textual programming systems. Compatibility with STM32F4-Discovery board has meant significant savings of time without reducing the power of the software.

RCP programming methodology used has facilitated the programming process. It has also reduced costs and has accelerated the development of control software of the hand.

On the other hand, the integration with high-level control systems has also been a success as can be observed in the project quoted above: "Implementation of a neural network-based electromyographic control system for a printed robotic hand" (8).

In addition, all the tests (even those from the second part of the project working with EMG signals) have been performed without invasion inside the body, an advantage for potential users of prostheses that can be developed from this project.

Finally, the prototype of the PCB designed has also provided the expected results and has fulfilled the requirements. It has been made by the services of the university and the components have been soldered manually by us in the course of work, so there have been no costly or time consuming processes.

6.2. Future work

In this last section, the results susceptible to improvements in this prototype will be described. Although the objectives have been met in general terms, the project has generated knowledge that must be taken into account for future work. The most notable recommendations and proposals will be listed below.

As mentioned, in order that the motor can rotate without difficulty, tendons should be a little slack, which implies the risk of coming into contact or out of their respective pulleys. As an improvement, partially closed channels could be implemented in pulleys to have more precisely controlled the threads.

It could be also developed a more universal and stable system pulleys that allow holding threads of different materials and thicknesses to investigate whether there are other more effective methods for transmitting the motion.

Another feature to improve would be the robustness of the pieces to overcome some mechanical problems. Investigating other materials, readjusting parameters of the slicer or using a different model of 3D printer (prevailing always criteria of low cost), are suggested ideas.

As for manipulation capabilities, the possibility to cover a wider range of movements to achieve a product more similar to a human hand could be analyzed. The human hand, especially in the palm, has a lot of passive joints that allow the adaptation to objects based on the efforts of the muscles acting on the fingers. In this way, an improved design that enables the hand adapts to different shapes based on this mechanism, is also proposed. In the same vein, adding a degree of freedom to the thumb would also produce more natural movements.

On the other hand, integrating all the electronics (board of reduced surface mount components, SMD) within the robotic arm, is advised. This would increase the degree of anthropomorphism dispensing with the need of additional cables.

So far, several recommendable ideas have been explained to improve the built robotic arm. However, the following paragraphs will describe suggestions to fit the components contained in the arm, into the hand, to jump to the prosthesis. The redesigning procedure is allowed because it is a feature of open-source designs.

At the beginning, regarding the motorization of the hand, it is proposed to redesign the integration of the servos so that the forearm is not strictly necessary. The built prototype has allowed studying a control system based on EMG signals for prostheses, but it could not become one of them. The precise movements to be achieved derive precisely from the muscles in the forearm. Therefore, a person with an amputation above the forearm could not have an accurate control of the prosthesis through this system. On the other hand, if the person has an amputation at the level of the hand, could use this type of prosthesis, but the device should not include the forearm, because it is not amputated.

Thus, inserting the motors within the palm, around the wrist or even into phalanges, this robotic hand could be really used as prosthesis. Although the look would not be so natural, the functionality of the device would be increased. In any case, it should be considered using smaller actuators or different ones, (based on SMAs –shape memory alloys-, for instance) (36) to further reduce the size and weight of the device.

Once modified and improved the design, it should be tested by real amputees. After all, a device produced for them should take into account their assessments and corrections in order to obtain a comfortable and useful prosthesis. In addition, to integrate the prosthesis on a stump, a socket has to be designed and implemented.

Finally, future works should also include the implementation of different tactile sensors in order that the user can receive any feedback. Strength or pressure sensors are required to avoid deformation or cracking of objects grasped by the hand. Position sensors are needed to move the hand exactly as the user wants. Temperature sensors are also useful to keep the amputated informed and to prevent the prosthesis from being damaged by excessive heat.

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Annex A: Stages of the work

The whole project can be divided in seven stages.

1. Preliminary study (contextualizing the project, setting the objectives, brainstorming ideas…): 4 hours.
2. Studying literature related to the field and learning to use computer tools (calibrating the printer, software configuration…): 18 hours.
3. Printing pieces and preprocessing: 94 hours.
4. Assembling the hand, coupling of actuators and insertion of tendons: 38 hours.
5. Designing and assembling the PCB board: 9 hours
6. Programming in Simulink and performing experimental tests: 51 hours.
7. Writing and correcting the report: 126 hours.

STAGES	HOURS
1	4
2	18
3	94
4	38
5	9
6	51
7	126
TOTAL:	**340**

Table 7. Project time

The project schedule can be studied in Table 8 in which the weeks of work and the tasks performed are related.

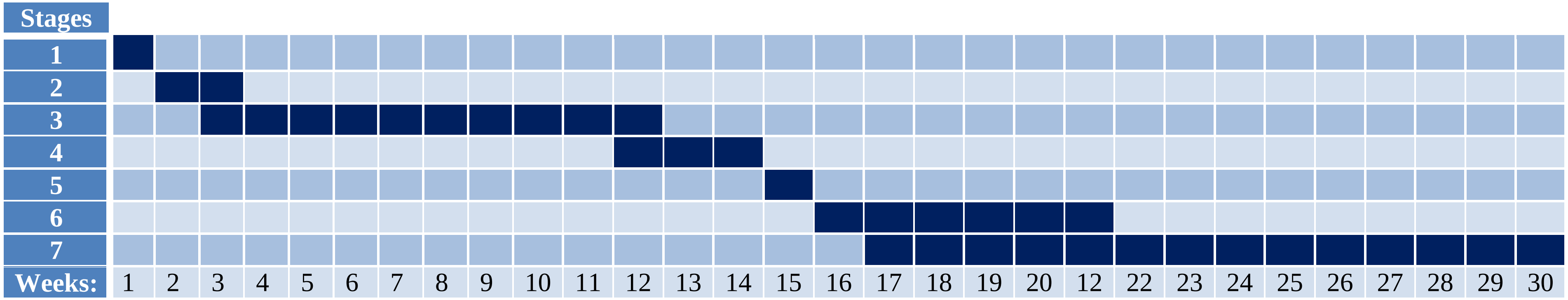


Table 8. Gantt chart

Annex B: Project Budget

In this section the budget of the project is detailed in four tables according to the nature of the costs.

	Unit	Unit Price (€)	Subtotal (€)
Robotic arm			
ABS plastic	750 g	0,02	15
Screws 2x10	30	0,035	1,05
Screws 3x12	10	0,043	0,43
Rods	3	0,05	0,15
Servomotors	6	5,69	34,14
Nylon fishing line	3 m	0,0094	0,02
Total:			**50,79**

Table 9. Robotic arm costs

	Unit	Unit Price (€)	Subtotal (€)
Electronic components			
Capacitors	24	0,05	1,20
µA 7806	6	0,57	3,42
Multifilament wire	2 m	0,10	0,20
USB cables	2	1,95	3,90
PCB	1	50	50
STM32F4-Discovery	1	14,28	14,28
TOTAL:			**73,00**

Table 10. Electronic components costs

	Unit cost (€)	Lifespan	Use	Cost (€)
Computing equipment				
Computer	630	60 months	10 months	105
3D Printer	425	60 months	5 months	35,41
Student Matlab license	69	48 months	3 months	4,31
OrCAD license	62,25	48 months	1 month	1,29
TOTAL:				**146,01**

Table 11. Computing equipment costs

	Hours	Price/Hour (€)	Subtotal (€)
Human resources			
PhD Engineer	3	50	150
Tutor, Engineer	50	45	2250
Technical Personnel	1	20	20
Engineering Student	340	20	6800
TOTAL:			**9220**

Table 12. Human resources costs

FINAL COSTS (€)	
Robotic arm	50,79
Electronic components	73
Computing equipment	146,01
Human resources cost	9.220
IVA 21%	56,65
TOTAL:	**9.546,45**

Table 13. Final costs

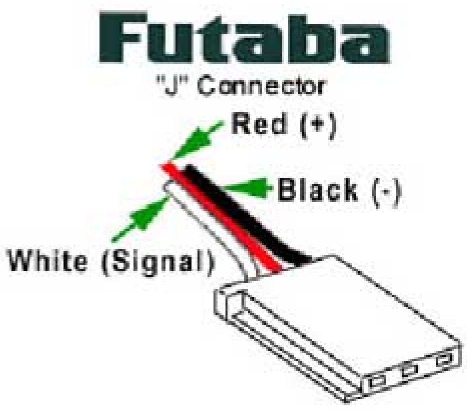
Annex C: Datasheets

1. ABS plastic
2. Servomotor Futaba S3003
3. Voltage regulator µA7806

ABS Material Data Sheet

Physical Properties	Metric	English	Comments
Density	1.04 g/cc	0.0376 lb/in³	Grade Count = 3
Melt Flow	18 - 23 g/10 min	18 - 23 g/10 min	Average = 21.3 g/10 min; Grade Count = 3
Mechanical Properties			
Hardness, Rockwell R	103 - 112	103 - 112	Average = 110; Grade Count = 3
Tensile Strength, Yield	42.5 - 44.8 MPa	6160 - 6500 psi	Average = 44 MPa; Grade Count = 3
Elongation at Break	23 - 25 %	23 - 25 %	Average = 24.3%; Grade Count = 3
Flexural Modulus	2.25 - 2.28 GPa	326 - 331 ksi	Average = 2.3 GPa; Grade Count = 3
Flexural Yield Strength	60.6 - 73.1 MPa	8790 - 10600 psi	Average = 68.9 MPa; Grade Count = 3
Izod Impact, Notched	2.46 - 2.94 J/cm	4.61 - 5.51 ft-lb/in	Average = 2.8 J/cm; Grade Count = 3
Electrical Properties			
Arc Resistance	120 sec	120 sec	Grade Count=1
Comparative Tracking Index	600 V	600 V	Grade Count=1
Hot Wire Ignition, HWI	15 sec	15 sec	Grade Count = 1
High Amp Arc Ignition, HAI	120 arcs	120 arcs	Grade Count = 1
High Voltage Arc-Tracking Rate, HVTR	25 mm/min	0.984 in/min	Grade Count = 1
Thermal Properties			
Maximum Service Temperature, Air	88 - 89 °C	190 - 192 °F	Average = 88.7°C; Grade Count = 3
Deflection Temperature at 1.8 MPa (264 psi)	88 - 89 °C	190 - 192 °F	Average = 88.7°C; Grade Count=3
Vicat Softening Point	100 °C	212 °F	Grade Count = 1
Flammability, UL94	HB	HB	Grade Count = 3

S3003 FUTABA SERVO



...S3003 FUTABA SERVO...

Detailed Specifications

Control System:	+Pulse Width Control 1520usec Neutral	Current Drain (4.8V):	7.2mA/idle
Required Pulse:	3-5 Volt Peak to Peak Square Wave	Current Drain (6.0V):	8mA/idle
Operating Voltage:	4.8-6.0 Volts	Direction:	Counter Clockwise/Pulse Traveling 1520-1900usec
Operating Temperature Range:	-20 to +60 Degree C	Motor Type:	3 Pole Ferrite
Operating Speed (4.8V):	0.23sec/60 degrees at no load	Potentiometer Drive:	Indirect Drive
Operating Speed (6.0V):	0.19sec/60 degrees at no load	Bearing Type:	Plastic Bearing
Stall Torque (4.8V):	44 oz/in. (3.2kg.cm)	Gear Type:	All Nylon Gears
Stall Torque (6.0V):	56.8 oz/in. (4.1kg.cm)	Connector Wire Length:	12"
Operating Angle:	45 Deg. one side pulse traveling 400usec	Dimensions:	1.6" x 0.8"x 1.4" (41 x 20 x 36mm)
360 Modifiable:	Yes	Weight:	1.3oz. (37.2g)

FAIRCHILD

September 2014

LM78XX / LM78XXA
3-Terminal 1 A Positive Voltage Regulator

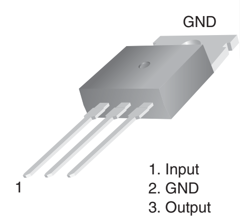
Features

- Output Current up to 1 A
- Output Voltages: 5, 6, 8, 9, 10, 12, 15, 18, 24 V
- Thermal Overload Protection
- Short-Circuit Protection
- Output Transistor Safe Operating Area Protection

Description

The LM78XX series of three-terminal positive regulators is available in the TO-220 package and with several fixed output voltages, making them useful in a wide range of applications. Each type employs internal current limiting, thermal shut-down, and safe operating area protection. If adequate heat sinking is provided, they can deliver over 1 A output current. Although designed primarily as fixed-voltage regulators, these devices can be used with external components for adjustable voltages and currents.

TO-220 (Single Gauge)



Ordering Information[1]

Product Number	Output Voltage Tolerance	Package	Operating Temperature	Packing Method
LM7805CT	±4%	TO-220 (Single Gauge)	-40°C to +125°C	Rail
LM7806CT				
LM7808CT				
LM7809CT				
LM7810CT				
LM7812CT				
LM7815CT				
LM7818CT				
LM7824CT				
LM7805ACT	±2%		0°C to +125°C	
LM7809ACT				
LM7810ACT				
LM7812ACT				
LM7815ACT				

Note:
1. Above output voltage tolerance is available at 25°C.

Block Diagram

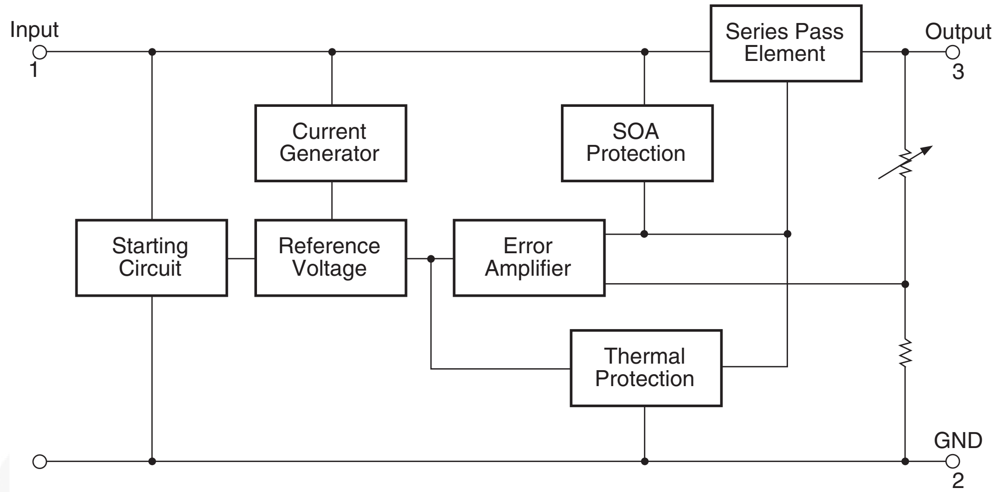


Figure 1. Block Diagram

Absolute Maximum Ratings

Stresses exceeding the absolute maximum ratings may damage the device. The device may not function or be operable above the recommended operating conditions and stressing the parts to these levels is not recommended. In addition, extended exposure to stresses above the recommended operating conditions may affect device reliability. The absolute maximum ratings are stress ratings only. Values are at T_A = 25°C unless otherwise noted.

Symbol	Parameter		Value	Unit
V_I	Input Voltage	V_O = 5 V to 18 V	35	V
		V_O = 24 V	40	
$R_{\theta JC}$	Thermal Resistance, Junction-Case (TO-220)		5	°C/W
$R_{\theta JA}$	Thermal Resistance, Junction-Air (TO-220)		65	°C/W
T_{OPR}	Operating Temperature Range	LM78xx	-40 to +125	°C
		LM78xxA	0 to +125	
T_{STG}	Storage Temperature Range		- 65 to +150	°C

Electrical Characteristics (LM7805)

Refer to the test circuit, -40°C < T_J < 125°C, I_O = 500 mA, V_I = 10 V, C_I = 0.1 µF, unless otherwise specified.

<table>
<tr><th>Symbol</th><th>Parameter</th><th colspan="2">Conditions</th><th>Min.</th><th>Typ.</th><th>Max.</th><th>Unit</th></tr>
<tr><td rowspan="2">V_O</td><td rowspan="2">Output Voltage</td><td colspan="2">T_J = +25°C</td><td>4.80</td><td>5.00</td><td>5.20</td><td rowspan="2">V</td></tr>
<tr><td colspan="2">I_O = 5 mA to 1 A, $P_O \leq$ 15 W,
V_I = 7 V to 20 V</td><td>4.75</td><td>5.00</td><td>5.25</td></tr>
<tr><td rowspan="2">Regline</td><td rowspan="2">Line Regulation[2]</td><td rowspan="2">T_J = +25°C</td><td>V_I = 7 V to 25 V</td><td></td><td>4.0</td><td>100.0</td><td rowspan="2">mV</td></tr>
<tr><td>V_I = 8 V to 12 V</td><td></td><td>1.6</td><td>50.0</td></tr>
<tr><td rowspan="2">Regload</td><td rowspan="2">Load Regulation[2]</td><td rowspan="2">T_J = +25°C</td><td>I_O = 5 mA to 1.5 A</td><td></td><td>9.0</td><td>100.0</td><td rowspan="2">mV</td></tr>
<tr><td>I_O = 250 mA to 750 mA</td><td></td><td>4.0</td><td>50.0</td></tr>
<tr><td>I_Q</td><td>Quiescent Current</td><td colspan="2">T_J = +25°C</td><td></td><td>5</td><td>8</td><td>mA</td></tr>
<tr><td rowspan="2">ΔI_Q</td><td rowspan="2">Quiescent Current Change</td><td colspan="2">I_O = 5 mA to 1 A</td><td></td><td>0.03</td><td>0.50</td><td rowspan="2">mA</td></tr>
<tr><td colspan="2">V_I = 7 V to 25 V</td><td></td><td>0.30</td><td>1.30</td></tr>
<tr><td>$\Delta V_O/\Delta T$</td><td>Output Voltage Drift[3]</td><td colspan="2">I_O = 5 mA</td><td></td><td>-0.8</td><td></td><td>mV/°C</td></tr>
<tr><td>V_N</td><td>Output Noise Voltage</td><td colspan="2">f = 10 Hz to 100 kHz, T_A = +25°C</td><td></td><td>42</td><td></td><td>µV</td></tr>
<tr><td>RR</td><td>Ripple Rejection[3]</td><td colspan="2">f = 120 Hz, V_I = 8 V to 18 V</td><td>62</td><td>73</td><td></td><td>dB</td></tr>
<tr><td>V_{DROP}</td><td>Dropout Voltage</td><td colspan="2">T_J = +25°C, I_O = 1 A</td><td></td><td>2</td><td></td><td>V</td></tr>
<tr><td>R_O</td><td>Output Resistance[3]</td><td colspan="2">f = 1 kHz</td><td></td><td>15</td><td></td><td>mΩ</td></tr>
<tr><td>I_{SC}</td><td>Short-Circuit Current</td><td colspan="2">T_J = +25°C, V_I = 35 V</td><td></td><td>230</td><td></td><td>mA</td></tr>
<tr><td>I_{PK}</td><td>Peak Current[3]</td><td colspan="2">T_J = +25°C</td><td></td><td>2.2</td><td></td><td>A</td></tr>
</table>

Notes:

2. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
3. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7806)

Refer to the test circuit, -40°C < T_J < 125°C, I_O = 500 mA, V_I = 11 V, C_I = 0.33 µF, C_O = 0.1 µF, unless otherwise specified.

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		5.75	6.00	6.25	V
		I_O = 5 mA to 1 A, $P_O \leq$ 15 W, V_I = 8.0 V to 21 V		5.70	6.00	6.30	
Regline	Line Regulation(4)	T_J = +25°C	V_I = 8 V to 25 V		5.0	120.0	mV
			V_I = 9 V to 13 V		1.5	60.0	
Regload	Load Regulation(4)	T_J = +25°C	I_O = 5 mA to 1.5 A		9.0	120.0	mV
			I_O = 250 mA to 750 mA		3.0	60.0	
I_Q	Quiescent Current	T_J = +25°C			5	8	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A				0.5	mA
		V_I = 8 V to 25 V				1.3	
$\Delta V_O/\Delta T$	Output Voltage Drift(5)	I_O = 5 mA			-0.8		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			45		µV
RR	Ripple Rejection(5)	f = 120 Hz, V_I = 8 V to 18 V		62	73		dB
V_{DROP}	Dropout Voltage	T_J = +25°C, I_O = 1 A			2		V
R_O	Output Resistance(5)	f = 1 kHz			19		mΩ
I_{SC}	Short-Circuit Current	T_J = +25°C, V_I = 35 V			250		mA
I_{PK}	Peak Current(5)	T_J = +25°C			2.2		A

Notes:

4. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
5. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7808)

Refer to the test circuit, -40°C < T_J < 125°C, I_O = 500 mA, V_I = 14 V, C_I = 0.33 µF, C_O = 0.1 µF, unless otherwise specified.

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		7.7	8.0	8.3	V
		I_O = 5 mA to 1 A, $P_O \leq$ 15 W, V_I = 10.5 V to 23 V		7.6	8.0	8.4	
Regline	Line Regulation(6)	T_J = +25°C	V_I = 10.5 V to 25 V		5	160	mV
			V_I = 11.5 V to 17 V		2	80	
Regload	Load Regulation(6)	T_J = +25°C	I_O = 5 mA to 1.5 A		10	160	mV
			I_O = 250 mA to 750 mA		5	80	
I_Q	Quiescent Current	T_J = +25°C			5	8	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A			0.05	0.50	mA
		V_I = 10.5 V to 25 V			0.5	1.0	
$\Delta V_O/\Delta T$	Output Voltage Drift(7)	I_O = 5 mA			-0.8		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			52		µV
RR	Ripple Rejection(7)	f = 120 Hz, V_I = 11.5 V to 21.5 V		56	73		dB
V_{DROP}	Dropout Voltage	I_O = 1 A, T_J = +25°C			2		V
R_O	Output Resistance(7)	f = 1 kHz			17		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_J = +25°C			230		mA
I_{PK}	Peak Current(7)	T_J = +25°C			2.2		A

Notes:

6. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
7. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7809)

Refer to the test circuit, -40°C < T_J < 125°C, I_O = 500 mA, V_I = 15 V, C_I = 0.33 µF, C_O = 0.1 µF, unless otherwise specified.

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		8.65	9.00	9.35	V
		I_O = 5 mA to 1 A, $P_O \leq$ 15 W, V_I = 11.5 V to 24 V		8.60	9.00	9.40	
Regline	Line Regulation[8]	T_J = +25°C	V_I = 11.5 V to 25 V		6	180	mV
			V_I = 12 V to 17 V		2	90	
Regload	Load Regulation[8]	T_J = +25°C	I_O = 5 mA to 1.5 A		12	180	mV
			I_O = 250 mA to 750 mA		4	90	
I_Q	Quiescent Current	T_J = +25°C			5	8	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A				0.5	mA
		V_I = 11.5 V to 26 V				1.3	
$\Delta V_O/\Delta T$	Output Voltage Drift[9]	I_O = 5 mA			-1		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			58		µV
RR	Ripple Rejection[9]	f = 120 Hz, V_I = 13 V to 23 V		56	71		dB
V_{DROP}	Dropout Voltage	I_O = 1 A, T_J = +25°C			2		V
R_O	Output Resistance[9]	f = 1 kHz			17		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_J = +25°C			250		mA
I_{PK}	Peak Current[9]	T_J = +25°C			2.2		A

Notes:

8. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
9. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7810)

Refer to the test circuit, -40°C < T_J < 125°C, I_O = 500 mA, V_I = 16 V, C_I = 0.33 µF, C_O = 0.1 µF, unless otherwise specified.

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		9.6	10.0	10.4	V
		I_O = 5 mA to 1 A, $P_O \leq$ 15 W, V_I = 12.5 V to 25 V		9.5	10.0	10.5	
Regline	Line Regulation(10)	T_J = +25°C	V_I = 12.5 V to 25 V		10	200	mV
			V_I = 13 V to 25 V		3	100	
Regload	Load Regulation(10)	T_J = +25°C	I_O = 5 mA to 1.5 A		12	200	mV
			I_O = 250 mA to 750 mA		4	400	
I_Q	Quiescent Current	T_J = +25°C			5.1	8.0	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A				0.5	mA
		V_I = 12.5 V to 29 V				1.0	
$\Delta V_O/\Delta T$	Output Voltage Drift(11)	I_O = 5 mA			-1		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			58		µV
RR	Ripple Rejection(11)	f = 120 Hz, V_I = 13 V to 23 V		56	71		dB
V_{DROP}	Dropout Voltage	I_O = 1 A, T_J = +25°C			2		V
R_O	Output Resistance(11)	f = 1 kHz			17		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_J = +25°C			250		mA
I_{PK}	Peak Current(11)	T_J = +25°C			2.2		A

Notes:

10. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
11. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7812)

Refer to the test circuit, -40°C < T_J < 125°C, I_O = 500 mA, V_I = 19 V, C_I = 0.33 µF, C_O = 0.1 µF, unless otherwise specified.

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		11.5	12.0	12.5	V
		I_O = 5 mA to 1 A, $P_O \leq$ 15 W, V_I = 14.5 V to 27 V		11.4	12.0	12.6	
Regline	Line Regulation[12]	T_J = +25°C	V_I = 14.5 V to 30 V		10	240	mV
			V_I = 16 V to 22 V		3	120	
Regload	Load Regulation[12]	T_J = +25°C	I_O = 5 mA to 1.5 A		11	240	mV
			I_O = 250 mA to 750 mA		5	120	
I_Q	Quiescent Current	T_J = +25°C			5.1	8.0	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A			0.1	0.5	mA
		V_I = 14.5 V to 30 V			0.5	1.0	
$\Delta V_O/\Delta T$	Output Voltage Drift[13]	I_O = 5 mA			-1		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			76		µV
RR	Ripple Rejection[13]	f = 120 Hz, V_I = 15 V to 25 V		55	71		dB
V_{DROP}	Dropout Voltage	I_O = 1 A, T_J = +25°C			2		V
R_O	Output Resistance[13]	f = 1 kHz			18		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_J = +25°C			230		mA
I_{PK}	Peak Current[13]	T_J = +25°C			2.2		A

Notes:

12. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
13. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7815)

Refer to the test circuit, -40°C < T_J < 125°C, I_O = 500 mA, V_I = 23 V, C_I = 0.33 µF, C_O = 0.1 µF, unless otherwise specified.

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		14.40	15.00	15.60	V
		I_O = 5 mA to 1 A, $P_O \le$ 15 W, V_I = 17.5 V to 30 V		14.25	15.00	15.75	
Regline	Line Regulation[14]	T_J = +25°C	V_I = 17.5 V to 30 V		11	300	mV
			V_I = 20 V to 26 V		3	150	
Regload	Load Regulation[14]	T_J = +25°C	I_O = 5 mA to 1.5 A		12	300	mV
			I_O = 250 mA to 750 mA		4	150	
I_Q	Quiescent Current	T_J = +25°C			5.2	8.0	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A				0.5	mA
		V_I = 17.5 V to 30 V				1.0	
$\Delta V_O/\Delta T$	Output Voltage Drift[15]	I_O = 5 mA			-1		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			90		µV
RR	Ripple Rejection[15]	f = 120 Hz, V_I = 18.5 V to 28.5 V		54	70		dB
V_{DROP}	Dropout Voltage	I_O = 1 A, T_J = +25°C			2		V
R_O	Output Resistance[15]	f = 1 kHz			19		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_J = +25°C			250		mA
I_{PK}	Peak Current[15]	T_J = +25°C			2.2		A

Notes:

14. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
15. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7818)

Refer to the test circuit, -40°C < T_J < 125°C, I_O = 500 mA, V_I = 27 V, C_I = 0.33 µF, C_O = 0.1 µF, unless otherwise specified.

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		17.3	18.0	18.7	V
		I_O = 5 mA to 1 A, $P_O \leq$ 15 W, V_I = 21 V to 33 V		17.1	18.0	18.9	
Regline	Line Regulation(16)	T_J = +25°C	V_I = 21 V to 33 V		15	360	mV
			V_I = 24 V to 30 V		5	180	
Regload	Load Regulation(16)	T_J = +25°C	I_O = 5 mA to 1.5 A		15	360	mV
			I_O = 250 mA to 750 mA		5	180	
I_Q	Quiescent Current	T_J = +25°C			5.2	8.0	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A				0.5	mA
		V_I = 21 V to 33 V				1.0	
$\Delta V_O/\Delta T$	Output Voltage Drift(17)	I_O = 5 mA			-1		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			110		µV
RR	Ripple Rejection(17)	f = 120 Hz, V_I = 22 V to 32 V		53	69		dB
V_{DROP}	Dropout Voltage	I_O = 1 A, T_J = +25°C			2		V
R_O	Output Resistance(17)	f = 1 kHz			22		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_J = +25°C			250		mA
I_{PK}	Peak Current(17)	T_J = +25°C			2.2		A

Notes:

16. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
17. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7824)

Refer to the test circuit, -40°C < T_J < 125°C, I_O = 500 mA, V_I = 33 V, C_I = 0.33 µF, C_O = 0.1 µF, unless otherwise specified.

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		23.00	24.00	25.00	V
		I_O = 5 mA to 1 A, $P_O \leq$ 15 W, V_I = 27 V to 38 V		22.80	24.00	25.25	
Regline	Line Regulation[18]	T_J = +25°C	V_I = 27 V to 38 V		17	480	mV
			V_I = 30 V to 36 V		6	240	
Regload	Load Regulation[18]	T_J = +25°C	I_O = 5 mA to 1.5 A		15	480	mV
			I_O = 250 mA to 750 mA		5	240	
I_Q	Quiescent Current	T_J = +25°C			5.2	8.0	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A			0.1	0.5	mA
		V_I = 27 V to 38 V			0.5	1.0	
$\Delta V_O/\Delta T$	Output Voltage Drift[19]	I_O = 5 mA			-1.5		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			120		µV
RR	Ripple Rejection[19]	f = 120 Hz, V_I = 28 V to 38 V		50	67		dB
V_{DROP}	Dropout Voltage	I_O = 1 A, T_J = +25°C			2		V
R_O	Output Resistance[19]	f = 1 kHz			28		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_J = +25°C			230		mA
I_{PK}	Peak Current[19]	T_J = +25°C			2.2		A

Notes:

18. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
19. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7805A)

Refer to the test circuit, 0°C < T_J < 125°C, I_O = 1 A, V_I = 10 V, C_I = 0.33 μF, C_O = 0.1 μF, unless otherwise specified.

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		4.9	5.0	5.1	V
		I_O = 5 mA to 1 A, P_O ≤ 15 W, V_I = 7.5 V to 20 V		4.8	5.0	5.2	
Regline	Line Regulation[20]	V_I = 7.5 V to 25 V, I_O = 500 mA			5.0	50.0	mV
		V_I = 8 V to 12 V			3.0	50.0	
		T_J = +25°C	V_I = 7.3 V to 20 V		5.0	50.0	
			V_I = 8 V to 12 V		1.5	25.0	
Regload	Load Regulation[20]	T_J = +25°C, I_O = 5 mA to 1.5 A			9	100	mV
		I_O = 5 mA to 1 A			9	100	
		I_O = 250 mA to 750 mA			4	50	
I_Q	Quiescent Current	T_J = +25°C			5	6	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A				0.5	mA
		V_I = 8 V to 25 V, I_O = 500 mA				0.8	
		V_I = 7.5 V to 20 V, T_J = +25°C				0.8	
$\Delta V_O/\Delta T$	Output Voltage Drift[21]	I_O = 5 mA			-0.8		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			42		μV
RR	Ripple Rejection[21]	f = 120 Hz, V_O = 500 mA, V_I =8 V to 18 V			68		dB
V_{DROP}	Dropout Voltage	I_O = 1 A, T_J = +25°C			2		V
R_O	Output Resistance[21]	f = 1 kHz			17		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_J = +25°C			250		mA
I_{PK}	Peak Current[21]	T_J = +25°C			2.2		A

Notes:

20. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
21. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7809A)

Refer to the test circuit, 0°C < T_J < 125°C, I_O = 1 A, V_I = 15 V, C_I = 0.33 µF, C_O = 0.1 µF, unless otherwise specified.

Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C	8.82	9.00	9.16	V
		I_O = 5 mA to 1 A, $P_O \leq$ 15 W, V_I = 11.2 V to 24 V	8.65	9.00	9.35	
Regline	Line Regulation[22]	V_I = 11.7 V to 25 V, I_O = 500 mA		6	90	mV
		V_I = 12.5 V to 19 V		4	45	
		T_J = +25°C, V_I = 11.5 V to 24 V		6	90	
		T_J = +25°C, V_I = 12.5 V to 19 V		2	45	
Regload	Load Regulation[22]	T_J = +25°C, I_O = 5 mA to 1.5 A		12	100	mV
		I_O = 5 mA to 1 A		12	100	
		I_O = 250 mA to 750 mA		5	50	
I_Q	Quiescent Current	T_J = +25°C		5	6	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A			0.5	mA
		V_I = 12 V to 25 V, I_O = 500 mA			0.8	
		V_I = 11.7 V to 25 V, T_J = +25°C			0.8	
$\Delta V_O/\Delta T$	Output Voltage Drift[23]	I_O = 5 mA		-1		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C		58		µV
RR	Ripple Rejection[23]	f = 120 Hz, V_O = 500 mA, V_I =12 V to 22 V		62		dB
V_{DROP}	Dropout Voltage	I_O = 1 A, T_J = +25°C		2		V
R_O	Output Resistance[23]	f = 1 kHz		17		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_J = +25°C		250		mA
I_{PK}	Peak Current[23]	T_J = +25°C		2.2		A

Notes:

22. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
23. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7810A)

Refer to the test circuit, 0°C < T_J < 125°C, I_O = 1 A, V_I = 16 V, C_I = 0.33 µF, C_O = 0.1 µF, unless otherwise specified.

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		9.8	10.0	10.2	V
		I_O = 5 mA to 1 A, $P_O \le$ 15 W, V_I = 12.8 V to 25 V		9.6	10.0	10.4	
Regline	Line Regulation[24]	V_I = 12.8 V to 26 V, I_O = 500 mA			8	100	mV
		V_I = 13 V to 20 V			4	50	
		T_J = +25°C	V_I = 12.5 V to 25 V		8	100	
			V_I = 13 V to 20 V		3	50	
Regload	Load Regulation[24]	T_J = +25°C, I_O = 5 mA to 1.5 A			12	100	mV
		I_O = 5 mA to 1 A			12	100	
		I_O = 250 mA to 750 mA			5	50	
I_Q	Quiescent Current	T_J = +25°C			5	6	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A				0.5	mA
		V_I = 12.8 V to 25 V, I_O = 500 mA				0.8	
		V_I = 13 V to 26 V, T_J = +25°C				0.5	
$\Delta V_O/\Delta T$	Output Voltage Drift[25]	I_O = 5 mA			-1		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			58		µV
RR	Ripple Rejection[25]	f = 120 Hz, V_O = 500 mA, V_I =14 V to 24 V			62		dB
V_{DROP}	Dropout Voltage	I_O = 1 A, T_J = +25°C			2		V
R_O	Output Resistance[25]	f = 1 kHz			17		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_J = +25°C			250		mA
I_{PK}	Peak Current[25]	T_J = +25°C			2.2		A

Notes:

24. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
25. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7812A)

Refer to the test circuit, 0°C < T_J < 125°C, I_O = 1 A, V_I = 19 V, C_I = 0.33 µF, C_O = 0.1 µF, unless otherwise specified.

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		11.75	12.00	12.25	V
		I_O = 5 mA to 1 A, P_O ≤ 15 W, V_I = 14.8 V to 27 V		11.50	12.00	12.50	
Regline	Line Regulation[26]	V_I = 14.8 V to 30 V, I_O = 500 mA			10	120	mV
		V_I = 16 V to 22 V			4	120	
		T_J = +25°C	V_I = 14.5 V to 27 V		10	120	
			V_I = 16 V to 22 V		3	60	
Regload	Load Regulation[26]	T_J = +25°C, I_O = 5 mA to 1.5 A			12	100	mV
		I_O = 5 mA to 1 A			12	100	
		I_O = 250 mA to 750 mA			5	50	
I_Q	Quiescent Current	T_J = +25°C			5	6	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A				0.5	mA
		V_I = 14 V to 27 V, I_O = 500 mA				0.8	
		V_I = 15 V to 30 V, T_J = +25°C				0.8	
$\Delta V_O/\Delta T$	Output Voltage Drift[27]	I_O = 5 mA			-1		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			76		µV
RR	Ripple Rejection[27]	f = 120 Hz, V_O = 500 mA, V_I =14 V to 24 V			60		dB
V_{DROP}	Dropout Voltage	I_O = 1 A, T_J = +25°C			2		V
R_O	Output Resistance[27]	f = 1 kHz			18		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_J = +25°C			250		mA
I_{PK}	Peak Current[27]	T_J = +25°C			2.2		A

Notes:

26. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
27. These parameters, although guaranteed, are not 100% tested in production.

Electrical Characteristics (LM7815A)

Refer to the test circuit, 0°C < T_J < 125°C, I_O = 1 A, V_I = 23 V, C_I = 0.33 µF, C_O = 0.1 µF, unless otherwise specified.

Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C	14.75	15.00	15.30	V
		I_O = 5 mA to 1 A, $P_O \le$ 15 W, V_I = 17.7 V to 30 V	14.40	15.00	15.60	
Regline	Line Regulation(28)	V_I = 17.4 V to 30 V, I_O = 500 mA		10	150	mV
		V_I = 20 V to 26 V		5	150	
		T_J = +25°C, V_I = 17.5 V to 30 V		11	150	
		T_J = +25°C, V_I = 20 V to 26 V		3	75	
Regload	Load Regulation(28)	T_J = +25°C, I_O = 5 mA to 1.5 A		12	100	mV
		I_O = 5 mA to 1 A		12	100	
		I_O = 250 mA to 750 mA		5	50	
I_Q	Quiescent Current	T_J = +25°C		5.2	6.0	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A			0.5	mA
		V_I = 17.5 V to 30 V, I_O = 500 mA			0.8	
		V_I = 17.5 V to 30 V, T_J = +25°C			0.8	
$\Delta V_O/\Delta T$	Output Voltage Drift(29)	I_O = 5 mA		-1		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C		90		µV
RR	Ripple Rejection(29)	f = 120 Hz, V_O = 500 mA, V_I =18.5 V to 28.5 V		58		dB
V_{DROP}	Dropout Voltage	I_O = 1 A, T_J = +25°C		2		V
R_O	Output Resistance(29)	f = 1 kHz		19		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_J = +25°C		250		mA
I_{PK}	Peak Current(29)	T_J = +25°C		2.2		A

Notes:

28. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
29. These parameters, although guaranteed, are not 100% tested in production.

Typical Performance Characteristics

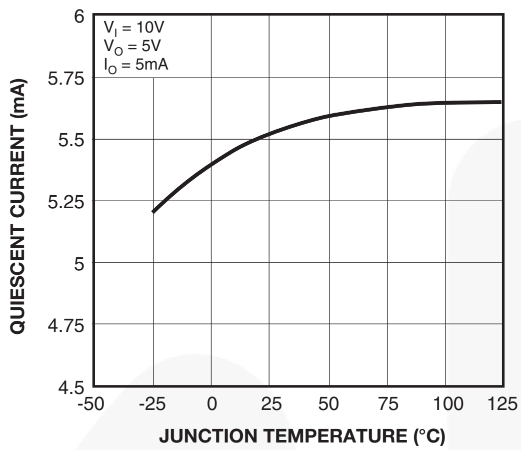


Figure 2. Quiescent Current

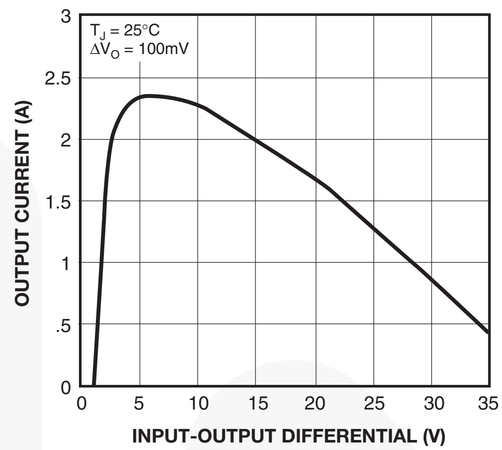


Figure 3. Peak Output Current

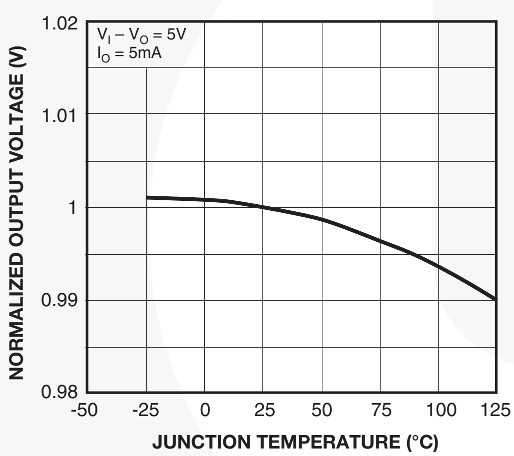


Figure 4. Output Voltage

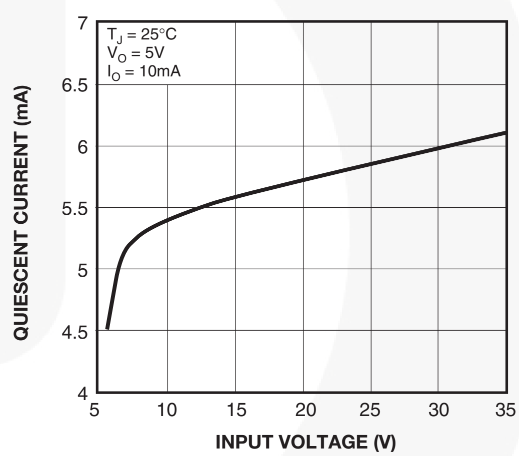


Figure 5. Quiescent Current

Typical Applications

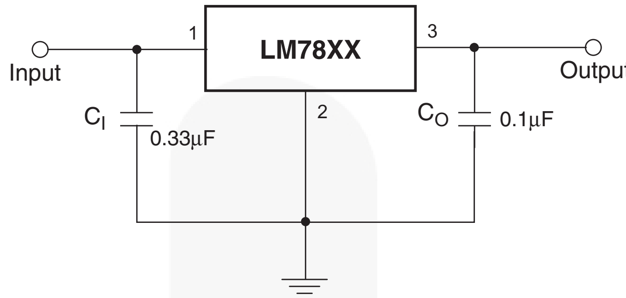


Figure 6. DC Parameters

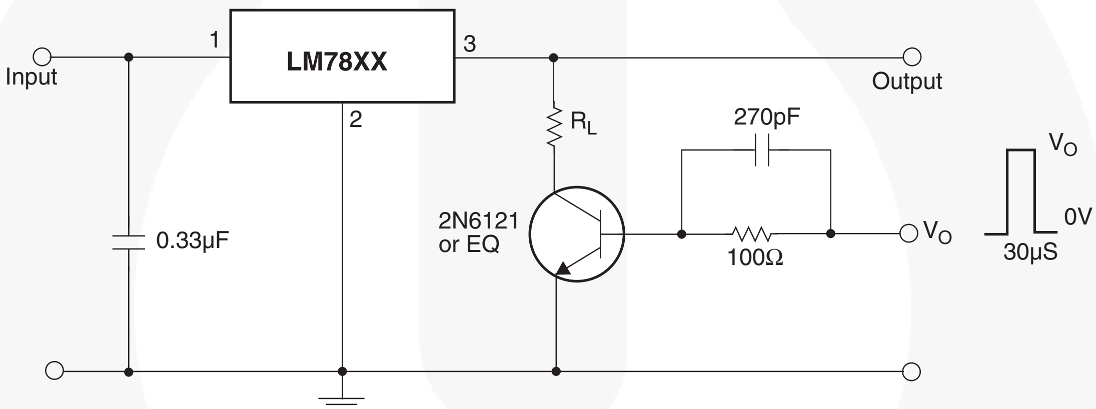


Figure 7. Load Regulation

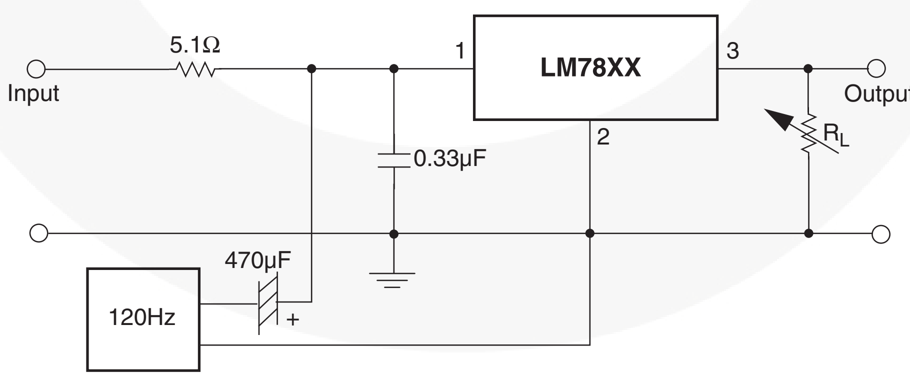


Figure 8. Ripple Rejection

Typical Applications (Continued)

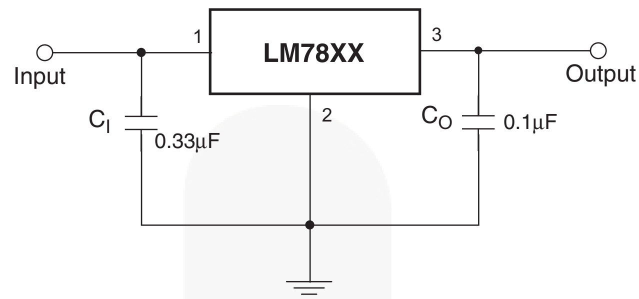


Figure 9. Fixed-Output Regulator

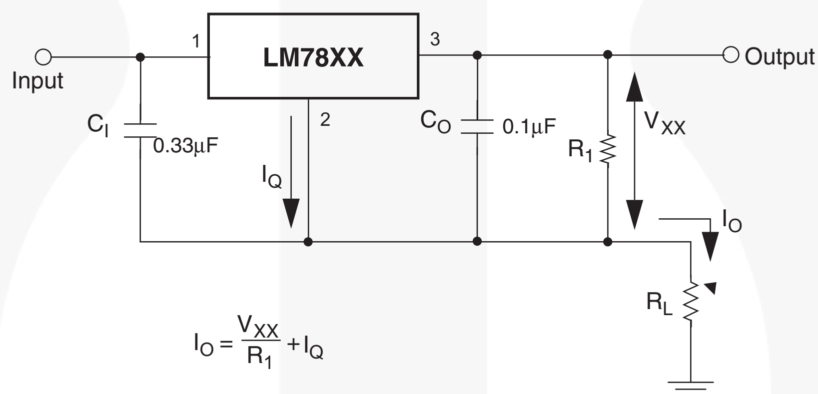


Figure 10. Constant Current Regulator

Notes:

29. To specify an output voltage, substitute voltage value for "XX". A common ground is required between the input and the output voltage. The input voltage must remain typically 2.0 V above the output voltage even during the low point on the input ripple voltage.
30. C_I is required if regulator is located an appreciable distance from power supply filter.
31. C_O improves stability and transient response.

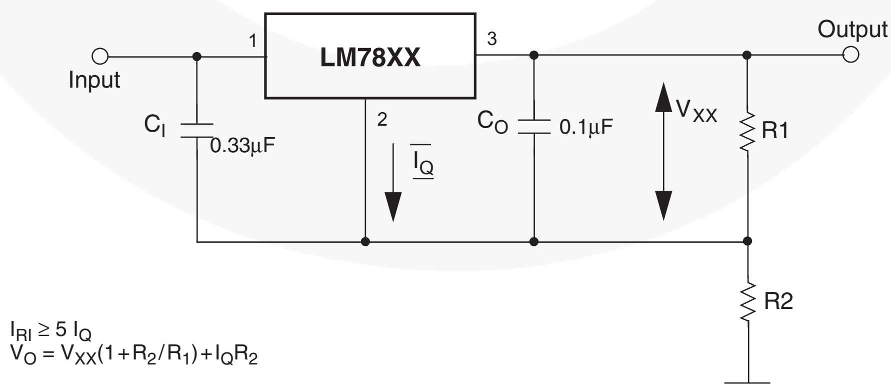


Figure 11. Circuit for Increasing Output Voltage

Typical Applications (Continued)

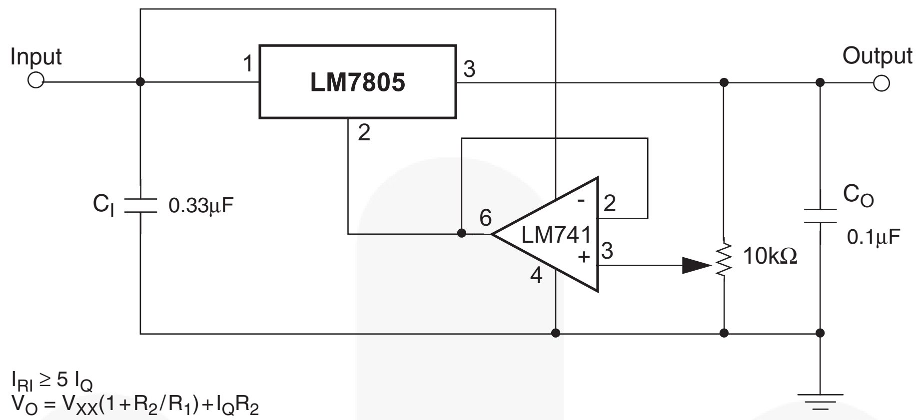


Figure 12. Adjustable Output Regulator (7 V to 30 V)

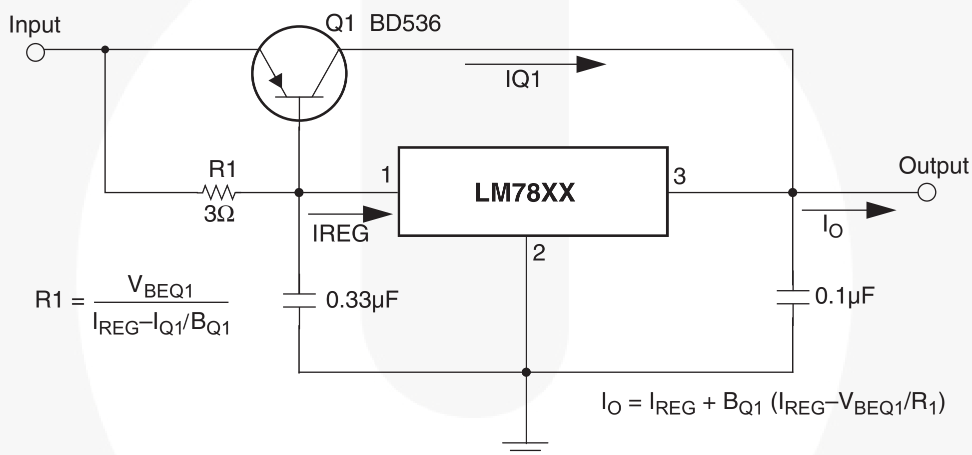


Figure 13. High-Current Voltage Regulator

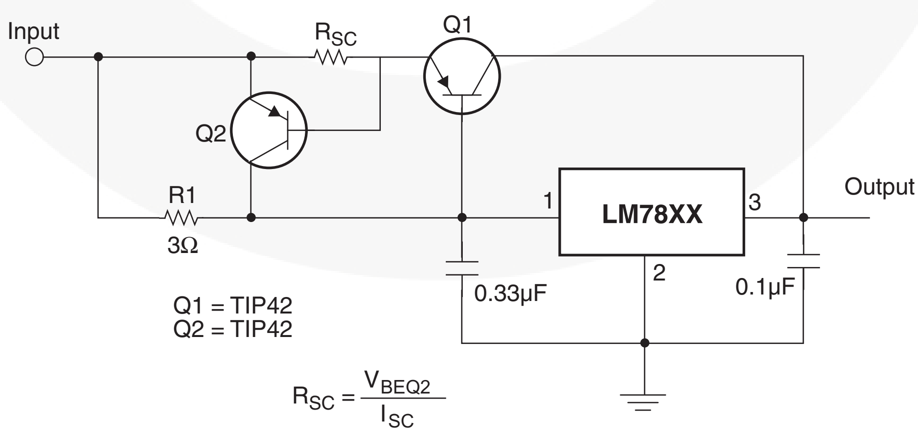


Figure 14. High Output Current with Short-Circuit Protection

Typical Applications (Continued)

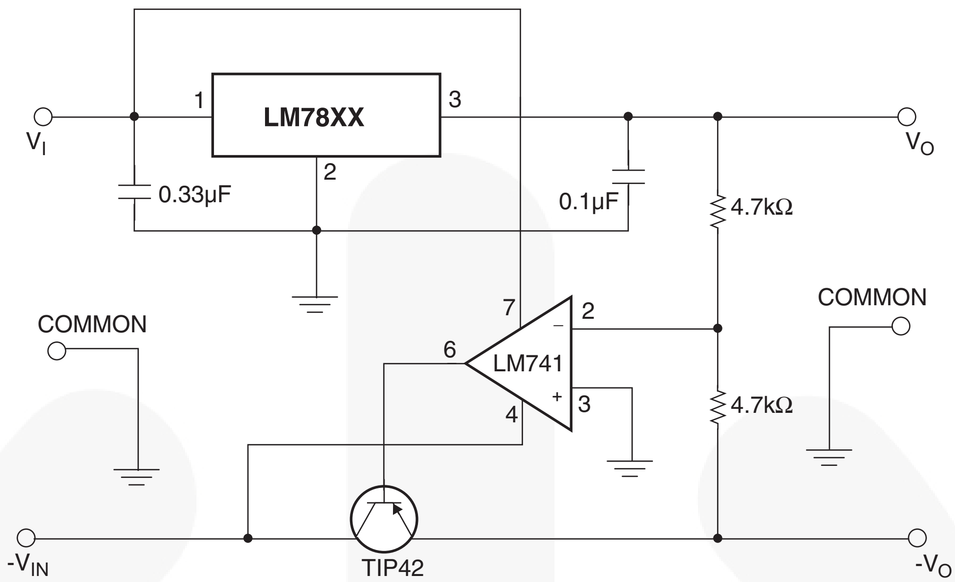


Figure 15. Tracking Voltage Regulator

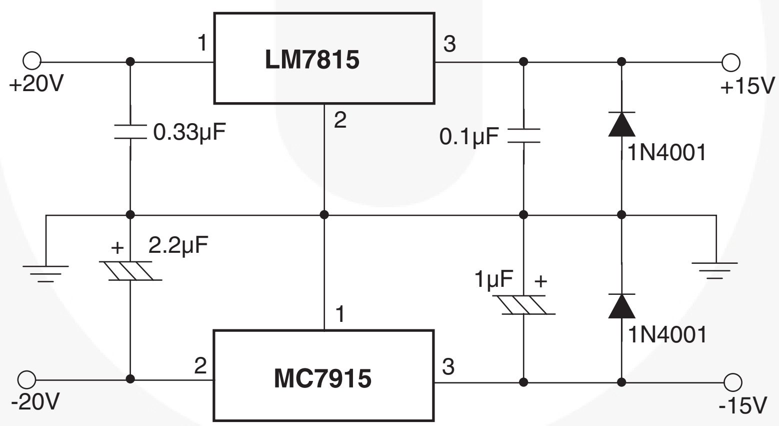


Figure 16. Split Power Supply (±15 V - 1 A)

Typical Applications (Continued)

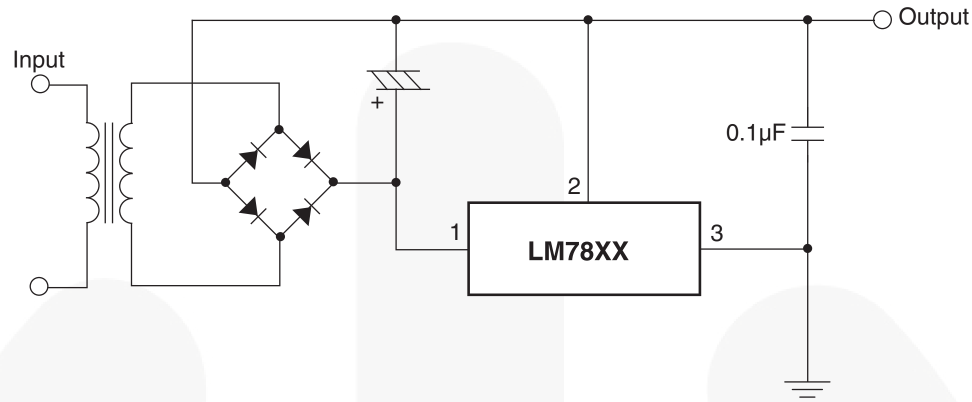


Figure 17. Negative Output Voltage Circuit

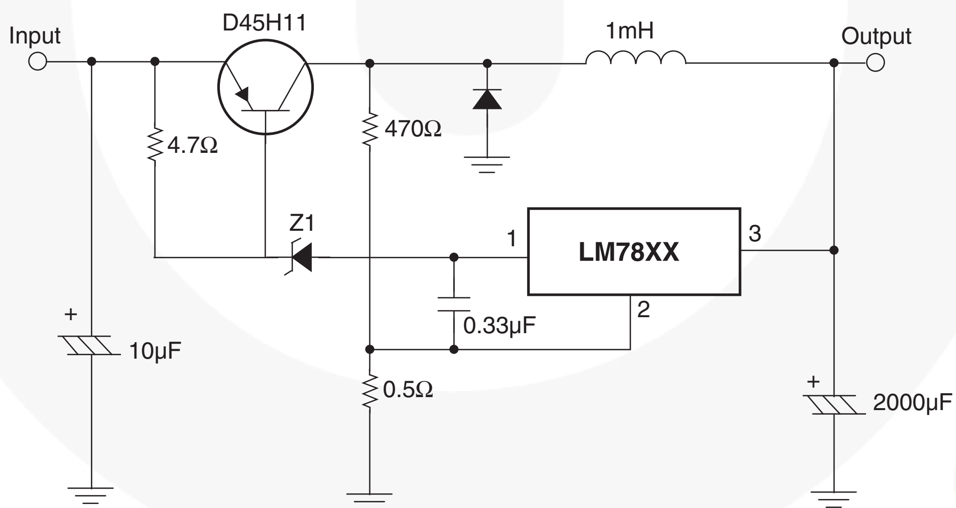
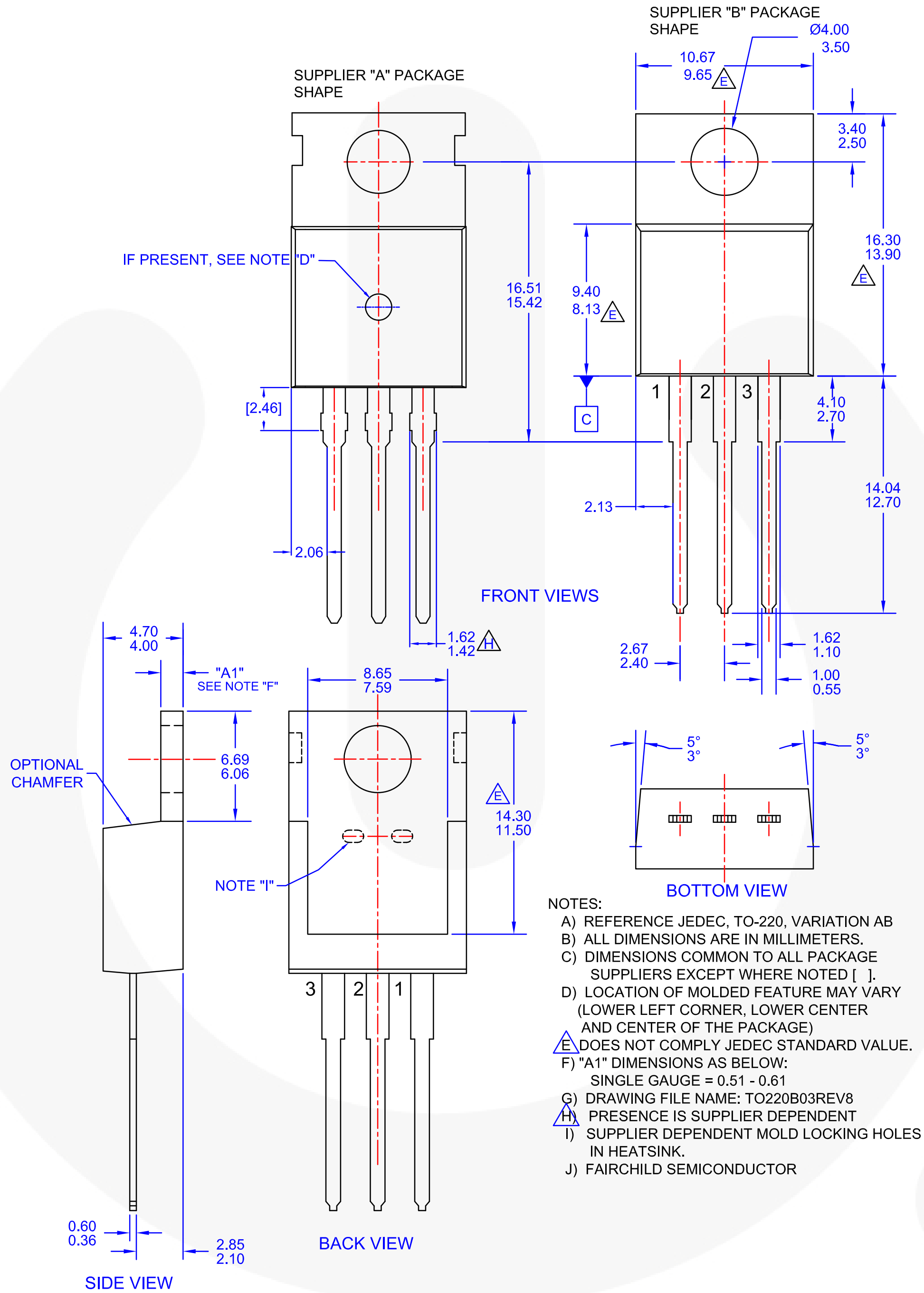


Figure 18. Switching Regulator

Physical Dimensions



NOTES:
- A) REFERENCE JEDEC, TO-220, VARIATION AB
- B) ALL DIMENSIONS ARE IN MILLIMETERS.
- C) DIMENSIONS COMMON TO ALL PACKAGE SUPPLIERS EXCEPT WHERE NOTED [ ].
- D) LOCATION OF MOLDED FEATURE MAY VARY (LOWER LEFT CORNER, LOWER CENTER AND CENTER OF THE PACKAGE)
- E DOES NOT COMPLY JEDEC STANDARD VALUE.
- F) "A1" DIMENSIONS AS BELOW: SINGLE GAUGE = 0.51 - 0.61
- G) DRAWING FILE NAME: TO220B03REV8
- H PRESENCE IS SUPPLIER DEPENDENT
- I) SUPPLIER DEPENDENT MOLD LOCKING HOLES IN HEATSINK.
- J) FAIRCHILD SEMICONDUCTOR

Figure 19. TO-220, MOLDED, 3-LEAD, JEDEC VARIATION AB (ACTIVE)

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